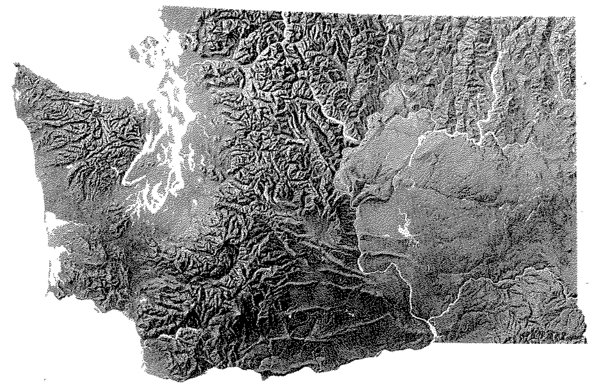
NATURAL RESOURCES



WASHINGTON GEOLOGY

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WASHINGTON STATE DEPARTMENT OF
Natural Resources
Jennifer M. Belcher - Commissioner of Public Lands
Kaleen Cottingham - Supervisor

Division of Geology and Earth Resources

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Cover photo: This 2-m-diameter Douglas-fir stump, discovered during excavations in Orting, Pierce County, was in a forest inundated by the Electron Mudflow about 600 years ago. The mudflow began when more than 200 million m^3 of debris was dislodged from the upper west flanks of Mount Rainier about 50 km away (channel distance), possibly by a steam explosion or regional earthquake. View is to the south-southeast. Photo by Patrick Pringle, 1993.

Staff Notes

William S. Lingley, Jr., has been promoted from Geologist 4 to Assistant State Geologist. He will oversee the Division's Surface Mining Regulatory Program.

Steve Palmer, our staff seismologist, has been promoted to Geologist 3.

Nancy Eberle, Cartographer 2, is on developmental assignment with the Forest Practices Division to gain more experience with the Geographic Information System (GIS).

Angela Stanton, Clerk Typist 3, has been promoted to Administrative Assistant 1 with the Division of Lands and Minerals. ***Karin Lang*** is temporarily filling Angela's old position handling accounts payable, travel, training, and payroll.

Robin Bennett has joined our staff for the summer as a Clerk Typist 2 to take Karin's place serving as receptionist, selling and keeping tabs on publications, reproducing open-file reports, and processing outgoing mail. Last summer Robin worked as a Clerk Typist 1 in DNR Personnel. Since graduating from Tumwater High School in 1993, she has been studying veterinary medicine at Washington State University.

Christina Sibbett will be assisting our clerical staff for two months this summer. This is Christina's first job with the State.

Pat McElroy, Deputy Supervisor for Resource Protection, retired June 30. DGER was one of three divisions for which Pat was responsible. His position will not be filled, and his duties will go to ***Art Stearns***, Deputy Supervisor for Operations. ■

Geowriting Short Course

The Geoscience Information Society (GIS), Association of Earth Science Editors (AESE), and the American Geological Institute (AGI) will cosponsor the short course "Geowriting: Guidelines for Writing and Referencing Technical Articles" at the 1994 Geological Society of America annual meeting in Seattle, WA. The course will cover methods of technical writing and bibliographic research in the geosciences.

The morning session will focus on technical report writing and will use the newly revised book "Geowriting", published by AGI, as a resource and text. The discussion will cover organization, getting started, editing, common grammatical problems, graphic presentation of data, and a brief introduction to common software packages available for word processing and graphics.

The afternoon session will focus on library research and referencing: the use of library catalogs and bibliographic databases, the compilation of references and the use of software for compiling references and bibliographies.

When: Saturday, October 22, 1994, 8:00 am–5:00 pm
Where: Seattle Sheraton Hotel, Seattle, WA
Limit: 35, preregistration required
Fee: Professional, $140 ($120 for early registration prior to August 1)
Student, $99
(includes handouts and a copy of "Geowriting")

For more information and to register, contact Julie Jackson, American Geological Institute, 4220 King Street, Alexandria, VA 22302; phone: 703-379-2480; fax: 703-379-7563; Internet e-mail: lar@aip.org.

Growth Management in Washington State

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Over recent decades, it has become apparent that, as a result of rapid population growth, our quality of life, the environment, and economic prosperity are at risk. Governor Booth Gardner began a coordinated response to this challenge by establishing the Washington State Growth Strategies Commission through Executive Order EO 89-08 on August 31, 1989. In 1990 the Legislature responded by enacting the landmark Growth Management Act to guide Washington State into the future. The Commission's final report "A Growth Strategy for Washington State" was released on September 25, 1990. This issue of *Washington Geology* is dedicated to describing some of the ways in which earth scientists and planners are involved in implementing the provisions of the Act and the recommendations of the Commission.

Effective July 1, 1990, the Act requires certain cities and counties exceeding a growth threshold to classify and designate agricultural, forestry, and mineral resource lands, as well as critical areas that have geological hazards. The Washington Department of Community Development (DCD), now the Department of Community, Trade and Economic Development, was designated as the state agency to adopt minimum guidelines and promulgate rules for the implementation of the Act.

During July 1990, DCD formed a Growth Management Technical Advisory Group to develop these minimum guidelines. The State Geologist was a member of this group and took a lead in developing a model ordinance pertaining to mineral resource lands. This recommended ordinance was sent to city and county planners on October 31, 1990, and published in the December 1990 issue of *Washington Geology* (vol. 18, no. 4).

After statewide public hearings and a comment period, DCD promulgated the minimum guidelines to classify agricultural, forest, mineral lands and critical areas as Washington Administrative Code (WAC) Chapter 365-190. The rules became effective April 15, 1991.

To assist local government, on March 19, 1991, DCD issued the "Planning Data Source Book for Resource Lands and Critical Areas". The model ordinance drafted by the State Geologist was included in this book.

Recognizing the complexity of and the time required to implement the Growth Management Act, the Legislature passed major amendments to the Act during the 1991 Session. One of the provisions called for a Committee on Natural Resources of Statewide Significance to make a report to the legislature. Under the auspices of the Department of Natural Resources (DNR), a temporary committee chaired by Bonnie Bunning was established to prepare a report on mineral resources of long-term commercial significance within and outside urban growth areas. The State Geologist participated on this committee. After receiving comments and holding two public hearings on the draft, the final report was submitted to the legislature on January 24, 1992. The report underscored the need for lands to be identified, classified, and protected to ensure resources are available in the future and to avoid the conflicts and controversies that we currently face between urban growth and mining.

As long as statutory minimums are met, the Growth Management Act gives local government considerable discretion on how the provisions are to be implemented. However, RCW 36.70A.106 does require transmittal of draft comprehensive plans to the State for review prior to adoption. The Public Lands Commissioner can appeal a plan that is not in compliance before the State Growth Planning Hearings Board under RCW 36.70A.310.

As interim and final draft growth management plans prepared by cities and counties were received by DNR during 1993 and early 1994, it was apparent that there was considerable inconsistency in the quality and effectiveness of the proposed plans. To assist local government in evaluating their plans, the Commissioner of Public Lands, Jennifer M. Belcher, issued on January 27, 1994, "Local Plan Review Guidelines". A summary of the guidelines follows:

(1) The plan designates and protects natural resources of long-term commercial significance in such a manner as to assure the potential for commercial production of forest, agricultural and mineral products for future generations.

(2) The plan has been coordinated and is consistent with the plans of other counties and cities where there are common borders involving natural resources of statewide significance.

(3) The plan provides equal treatment of State lands; that State lands are not unfairly designated to fill the need for natural resources of long-term commercial significance, habitat, recreation, and open space while allowing private landowners to convert to development.

(4) The State's proprietary interests are protected by the plan, and such interests can be managed for their respective resource and ecosystem values without major conflict.

(5) The DNR's legislative authority to administer statewide regulatory programs is recognized in the comprehensive plan—for example, forest practices, surface mining, and wildfire suppression and protection.

References Cited

Lasmanis, Raymond, 1990, Growth Management Act of 1990 and mineral resource lands: Washington Geology, v. 18, no. 4, p. 2.

Washington Department of Community Development, 1991, Planning data source book for resource lands and critical areas: Washington Department of Community Development, 1 v.

Washington State Growth Strategies Commission, 1990, A growth strategy for Washington State; Final report: Washington State Growth Strategies Commission, 60 p. ■

Geologic Hazards and the Growth Management Act

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INTRODUCTION

Washington is situated in a tectonically active environment at the western margin of North America and has climatic-vegetal zones that range from alpine to rain forest to shrub-steppe. Consequently, it has a broad spectrum of environmental hazards associated with earthquakes, landslides, volcanoes, wind and rain storms, and human activity. The lives, property, and productivity at risk are increasing as development moves into previously marginal lands.

In response to the problems associated with rapid urbanization and sprawl, the state legislature passed the Growth Management Act of 1990, which mandated comprehensive planning in the largest and fastest-growing jurisdictions. Recognizing that avoidable environmental hazards cost lives and money, the legislation directed all cities and counties to delineate critical areas (including those subject to geologic and hydrologic hazards) as an initial step of their planning and to formulate regulations governing development in such areas. It also required that natural-resource lands, including those containing economic mineral deposits, be identified and conserved.

Geoscientists (such as geologists, hydrologists, and soil scientists) have long been involved in evaluating natural hazards and resources. Processes initiated by the GMA have created new opportunities for incorporating earth-science information into land-use planning.

THE PLANNING PROCESS

Urban and regional planning grew out of the progressive movements of the late 19th and early 20th centuries, expressions of the desire to organize an increasingly urban-industrial society to provide decent housing and working conditions while preserving the natural beauty and amenities of the land. Planning was seen as a means of rationalizing development and construction in the rapidly growing cities of Europe and North America. The first zoning laws in the United States were enacted in 1916, at the instigation of landowners trying to protect themselves and their property from obnoxious neighboring uses. The Supreme Court upheld these ordinances as a protection of property rights, rather than the limitation they are sometimes characterized as being.

Public planning is "the coordination for public benefit of the design, construction, and operation of the many publicly-provided services that together make up the physical community" (Legget, 1973). The authority of government agencies to conduct planning ultimately derives from the police powers, the duty and right of government to protect the public health, safety, and welfare. An additional duty, not enshrined in law but equally germane, is the obligation of government agencies to protect the public purse, in this case from the unnecessary costs that can be associated with unplanned growth. Private entities also conduct planning when considering large development projects, some of which are in effect small cities. Plans can deal with single functions, such as parks, drainage, or transportation; or they can be comprehensive, treating all aspects of land use and circulation within a jurisdiction.

Land-use patterns are the result of many complex and interacting factors, and planners must have enough understanding of the local determinants that they can manipulate them to achieve the goals of the community (Howard and Remson, 1978). Much of human geography is a consequence of the multitude of personal and economic choices regarding location of homes, farms, and factories. Until the past few decades, most planning (whether by public agencies or private developers) dealt primarily with the social and economic determinants of land use, in an attempt to direct financial and political decisions toward some objectives, typically entailing development and growth.

However, there are also important physical determinants of land use. The locations of most towns can be ascribed to one or more attributes of the land that encouraged people to settle there. Perhaps it was some terrain characteristic that made for easy transportation, such as a site by a bay, a river crossing, or a pass through the mountains; or, it may have been the presence of good soils or exploitable mineral deposits (Fig. 1). While nature provides many such resources that encourage settlement, it also places some limits on land use, in the form of costs and risks from hazardous conditions. When land was abundant, these could be avoided wherever they were recognized (usually after sad experience with their disastrous effects). But other considerations became more important, such as access to roads and railroads, the presence of energy sources, or the very presence of cities and their concentrations of industrial and commercial activities.

As urban planning was being invented, the ability to overcome natural limitations was becoming greater, so the physical restrictions on land use were given less importance in planning. The dominance of money and engineering extended to the point that examination of the natural environment could be completely ignored in many planning texts in the 1950s and early 1960s (Legget, 1973). This neglect was soon replaced with a growing recognition that natural resources and hazards are critical considerations in land use, and thus in land-use planning. Along with this has come the realization that it is easier and cheaper to prevent problems than to fix them once they have occurred. In 1969, Ian McHarg showed in his seminal *Design with Nature* how environmental information could be generated and incorporated into planning and landscape architecture.

The first step in the planning process is definition of the problems to be addressed and the scope and objectives of the program to deal with them. Then, early on, information regarding the relevant physical, social, economic, and political land-use determinants should be collected (Fig. 2). This step should include an inventory of natural conditions, particularly the geologic and hydrologic processes that could constitute hazards or resources, and their areal distribution, magnitudes, and probabilities of recurrence. Each element of a comprehensive plan (land use, transportation, utilities, etc.) should incorporate pertinent information about natural conditions and hazards and lead to the designation of areas more or less suitable for various uses.

Implementation of the plan begins with public hearings before a planning commission, leading to adoption of the plan by the city or county council. Subsequent legislative, executive, and administrative actions include adoption of regulatory measures, such as zoning and subdivision ordinances and grading and building codes; land purchase and construction to provide public buildings, services, and amenities; and financing of public expenditures, through bonds, formation of local improvement districts, utility fees, etc.

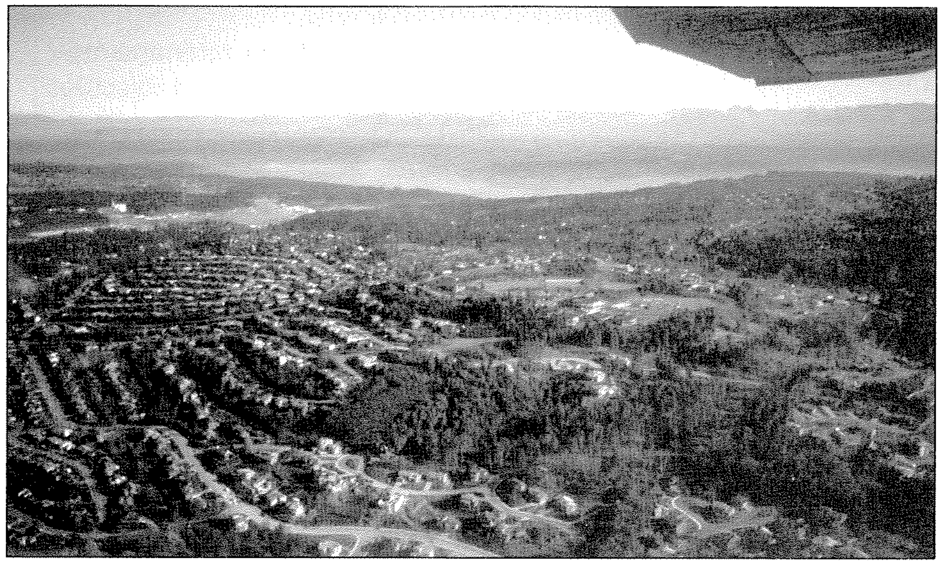

Figure 1. Geologic opportunities and limitations affect land use. In eastern King County, lands that were once used for producing and transporting coal and timber are now suburbs, served by a major highway (Interstate 90) (upper left) and enjoying the amenities of Lake Sammamish and views of the Cascades. But the natural conditions that encourage development can also introduce hazards: in this area, landslides in the ravines, collapse of abandoned coal mines, and flooding from increased runoff.

A private planning process would be somewhat different. For example, in a proposal for a planned unit development, information about environmental, economic, and social conditions would be prepared to help the developer evaluate parcels of land and decide on appropriate purchases. This information would then be used in plans and other documents submitted to public authorities, financial institutions, and eventually buyers for their approval.

Ultimately, both public and private projects must be reviewed for conformity with the plan, associated zoning codes, and other laws. In addition, most planning measures and projects are actions subject to review under the State Environmental Policy Act (SEPA).

The planning process should include development of broad-based agreement on the acceptable risks in relation to benefits associated with each hazard and resource. In particular, the nature and geographic distribution of important or sensitive lands should be considered in planning decisions such as zoning (which controls the specific distribution of various uses) and the siting of major facilities. Technical specialists should be involved in all parts of this process *and* in project review after adoption of the plan.

The first planning enabling act in Washington was approved by the state legislature in 1959. This and subsequent legislation allowed cities and counties to set up planning commissions and departments and to adopt plans and zoning ordinances. In response, many cities and counties prepared comprehensive plans, and most adopted zoning ordinances or other kinds of land-use controls. Nevertheless, Washington's rapid population growth in the 1980s resulted in poorly controlled sprawl in the urban fringe in the Puget Lowland, the Spokane Valley, Clark County, and other areas.

In 1990, the legislature found that there are economic and environmental costs to unplanned development, and it passed the Growth Management Act (Chap. 36.70A RCW, as amended in 1991) in order to promote greater efficiency in land development, controlled and sustainable growth, and environmental protection. The Act mandated that certain counties and their cities must prepare comprehensive plans, defined the elements that should go into them, and set up procedures for public participation, intergovernmental coordination, adoption, appeal, and amendment. Plans must include designation of urban growth areas (UGA) around existing cities and towns: urban services are to be provided only inside the UGAs during the lifetime of the plans, with low-density uses located outside them.

With regard to physical conditions, the Act defined a set of critical and resource lands that must be classified and designated in all cities and counties, and it mandated that the local jurisdictions adopt regulations to control urban development in designated areas. The agency now known as the Department of Community, Trade and Economic Development (DCTED) was directed to adopt guidelines (Chap. 365-190 WAC) for local governments to consider in carrying out the Act.

GEOLOGY, HAZARDS, AND PLANNING

Earth scientists have routinely applied geologic and hydrologic knowledge to the evaluation of resources and hazards, particularly since the organization of state and federal geological surveys in the 1800s (1890 in Washington). The participation of geologists in land-use planning increased with their expanding roles in civil construction, in development of policy on water resources and related issues in the 1930s, with urban development after World War II, and with the growth of environmental awareness in the 1950s and 1960s. There was a natural evolution from involvement with large

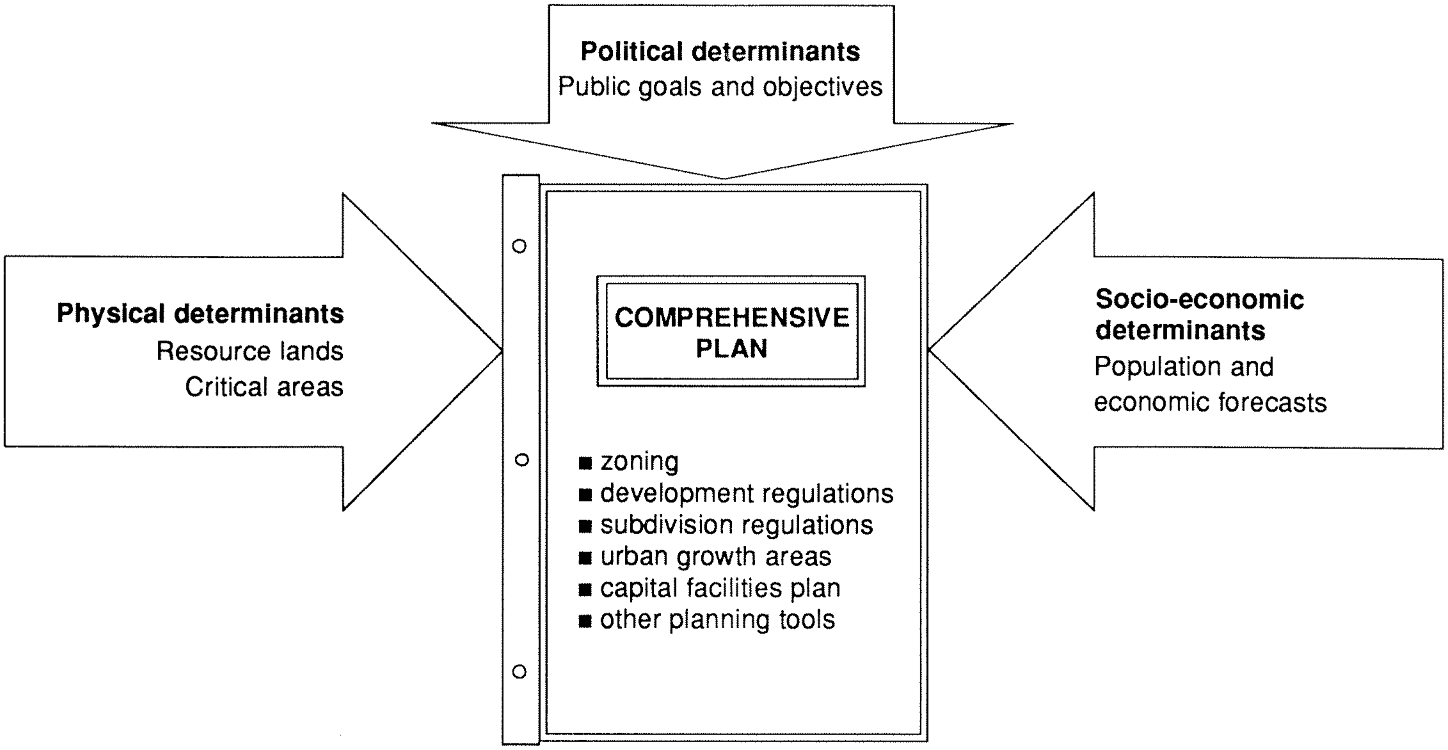

Figure 2. Information is necessary for the creation of a comprehensive plan. In particular, understanding of the physical controls on land use is important to many of the elements of the plan.

construction projects to aiding the predevelopment surveys for larger developments and even whole new towns.

However, for a long time economic and social factors overshadowed the natural elements in planning, and the potential contributions of geoscientists were ignored in most urban and regional plans. But by the time *Design with Nature* appeared in 1969, earth-science information was being adapted or produced for use in planning efforts in many parts of the country. In the 1950s and 1960s, engineering geology and environmental geology were emerging as important subfields: the Engineering Geology Branch of the U.S. Geological Survey (USGS) was conducting studies in several cities (McGill, 1964), and many more scientists were employed providing information for urban and regional planners. Books such as Flawn's *Environmental Geology* (1970) and Legget's *Cities and Geology* (1973) gave impetus to these new specialties.

Despite the many kinds of geologic resources and hazards in Washington, until recently the generation of geologic information for planning in this state has been limited and mostly piecemeal. Geologists have conducted numerous studies applicable to planning, but most have been for individual construction projects (for example, dams and nuclear facilities), in response to particular disasters (such as the eruption of Mount St. Helens), or focused on specific hazards (landslide and flood-plain investigations). (See Galster, 1989.) Some pilot projects, though, have been more extensive or predictive in nature. Beginning in about 1972, Division of Geology and Earth Resources (DGER) staff and contractors carried out several planning- and hazard-related studies and prepared interpretive maps for a few parts of the state (including Mason, Thurston, and eastern Jefferson Counties, and the Gig Harbor Peninsula). The Department of Ecology, with assistance from other agencies (including DGER), created an atlas for the inland coastal zone in 1972–80. The USGS's Earth Sciences Applications program examined the Puget Sound region in 1978–82, producing many basic and applied geologic maps, particularly for the Port Townsend 1:100,000 quadrangle.

Some efforts were explicitly for planning purposes. In 1980 the King County Planning Department prepared an atlas of maps delineating areas susceptible to various natural hazards, in order to implement the county sensitive-areas ordinance; the Basin Planning Program generated initial studies of hydrologic and geomorphic conditions in western King County in 1986–87. However, there has been nothing in Washington as thorough as the USGS work in the San Francisco Bay region or the environmental-geology reports prepared for many Oregon counties by the Oregon Department of Geology and Mineral Industries. Some local jurisdictions have used geologic and geotechnical experts (commonly consultants and volunteers) in planning and project review, but few geologists are employed on local planning or public-works staffs.

Ideally, geologic contributions to the planning process can help decision-makers and the citizenry recognize the restrictions that nature places on land use. The consequences of ignoring geologic and hydrologic conditions can include death, property damage, loss of commercial and governmental functions (all of which commonly result in lawsuits), loss of economic opportunities, and the public and private costs of repairing the damage from natural disasters. The existence of assorted geologic conditions, resources, and hazards affects many of the planning strategies and tools that can be used, ranging from requests for additional evaluations of certain lands to exclusion of some uses from hazardous areas. Therefore, earth-science information should be generated prior to or early in the process, as part of the study of land-use determi-

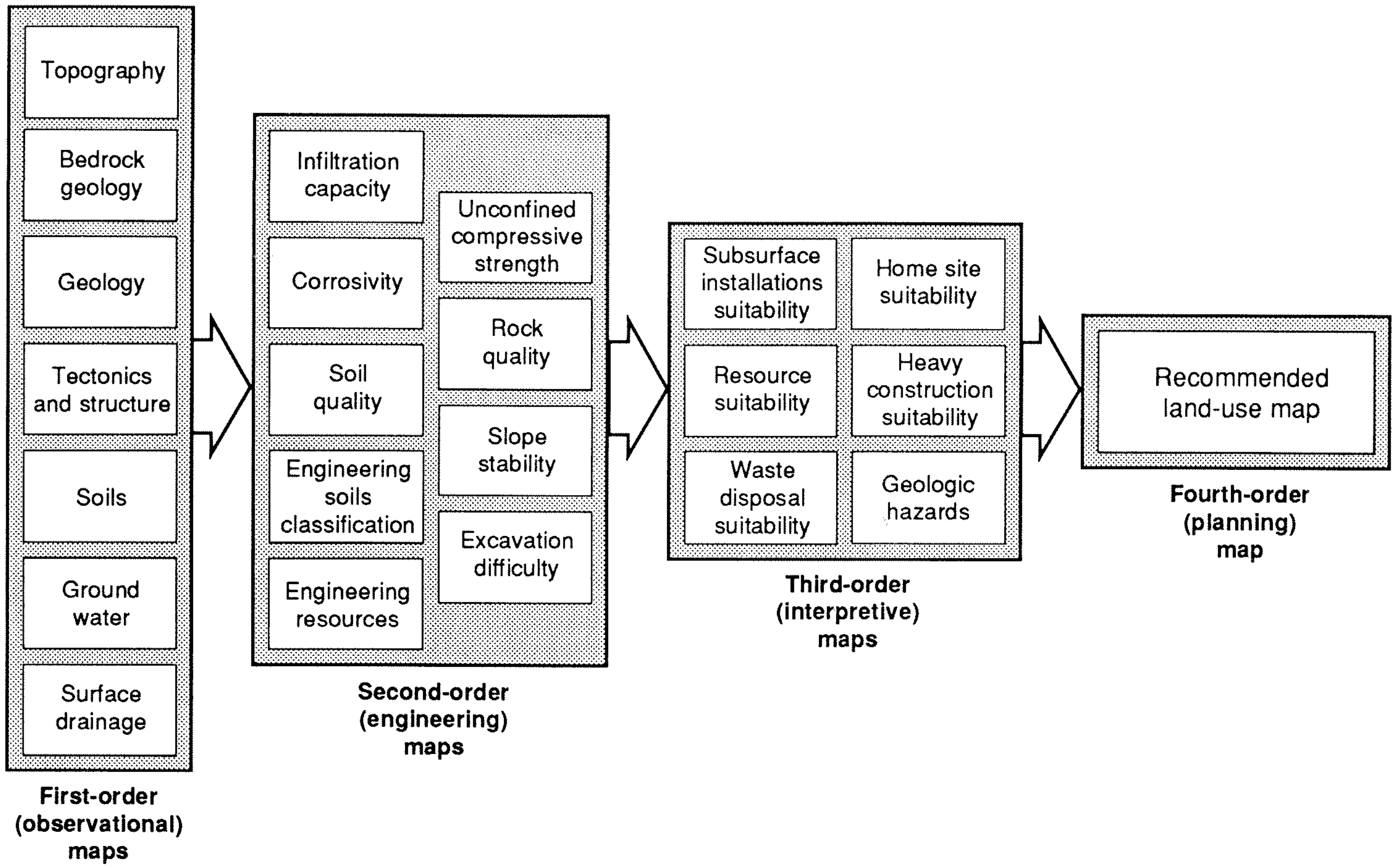

Figure 3. Ordering of geologic information for land-use planning. First-order maps show basic information, but they require much interpretation to be used for decision-making; third- and fourth-order maps provide interpretations, but the users must rely on those who created them. (Adapted from Mathewson and Font, 1974.)

nants, so that it can inform the many planning decisions that depend on understanding of the physical environment.

Some of the varieties of information that can be contributed by earth scientists are illustrated in Figure 3. Most of the basic observational studies of geology, soils, and hydrology are performed by public-agency scientists (those in the USGS, Washington Department of Natural Resources, or Soil Conservation Service, for example) outside of any particular planning or development program, but some investigations may be conducted for specific projects. On the other hand, interpretive studies are typically done in order to translate basic knowledge into forms that can help planners and engineers determine the physical advantages and limitations of an area, especially the best and worst lands for various uses. Such information may be incorporated into planning maps and documents that summarize the data about the physical environment into recommendations of optimal uses for a region. This would be combined with input regarding the other land-use determinants, the goals of the community, and the strategies adopted by the city or county into a comprehensive or functional plan that could then be the guiding document for implementation through zoning, development regulation, etc.

The function of maps in planning is crucial, but sometimes underappreciated. Most environmental scientists understand the utility of maps for analysis and in presenting data for both scientific communication and public decision-making (Robinson and Spieker, 1978; Bernkopf and others, 1993). In general, planners are also proficient in the creation and use of maps, both as tools of their work and as media to display the results. However, sometimes the potential effectiveness of a map is outweighed by considerations such as the lack of complete information, the fear of offending interest groups or property owners, or merely the shortage of time or staff to produce usable maps. None of these invalidates the great value of maps in the planning process.

Another potential problem is that scientists' and planners' conceptions of maps may be different, perhaps at opposite ends of the flow system shown in Figure 3. Geologists usually deal with the basic observational maps. Planners may be more accustomed to those depicting current or recommended land uses and may want hazard or suitability maps that summarize, translate, and interpret the basic information. However, users of interpretive maps are at the mercy of those who make the interpretations. There is an important role for people who are conversant in earth sciences, engineering, planning, and the interactions among these fields in the preparation and interpretation of planning maps. Also, the increasing use of computer-based geographic information systems in all disciplines is making the manipulation of mapped data easier and thus more routine.

After plans are completed, geoscientists and geotechnical engineers still have several functions in the implementation stage. Commonly they work as consultants for people and firms proposing construction or development projects, providing more detailed or site-specific information about geologic, soil, and hydrologic conditions relating to their clients' proposals. On the public side, earth scientists also get involved in writing regulations to govern development (particularly for areas susceptible to landslides, flooding, and other natural processes) and in reviewing project documents. In such roles they have to interact with other scientists, planners, and engineers in order to create regulatory or engineering solutions for many potential situations or to determine the effects of contemplated uses and development. This may require geologists to move from applied scientific investigation, to which they are reasonably accustomed, into more political tasks for which they generally are not as prepared.

THE GMA AND GEOLOGICAL INFORMATION

The Growth Management Act (GMA) has changed the planning situation in Washington and provided several new opportunities for incorporating earth-science information into the process. Recognizing the continuing incidence of death, damage, and lawsuits from natural hazards as development moves into formerly marginal lands, not to mention simply poor and costly land-use decisions, the Act directed that resource lands and critical areas be designated by all jurisdictions and used as the basis for development regulations and other planning strategies. Some of these areas are designated to protect the land for certain uses (for example, agriculture or wildlife habitat); others are to protect people from the unpleasant things that can occur in certain parts of the landscape (the geologically hazardous areas). In those jurisdictions that prepare comprehensive plans, the resource lands and critical areas are explicitly to be considered early in the process and duly regarded in setting the urban growth boundaries, zoning, etc.

Classification of critical and resource lands was based on the Act and on the guidelines written by DCTED. The latter were modeled on the King County sensitive areas ordinance, modified (with the help of many geoscientists and engineers) to be applicable to the entire state. Each city and county was to classify lands on the basis of local conditions and to designate the lands so classified. Designation should involve definition of areas susceptible to natural hazards, particularly by mapping of those hazards that are geographically locatable. Written criteria or performance standards can be useful for regulation, but maps are necessary for some planning functions, such as zoning. Some cities and counties experienced problems in the classification and designation processes due to misunderstanding of the guidelines, shortage of funds or staff technical expertise, and lack of existing maps and other information. When county and city planners looked for maps of landslides or seismic liquefaction or volcanic hazards for their areas, they were usually disappointed and had to recruit technical help to quickly adapt the available information. In some instances, no new maps were created, and other parts of the process suffered from the lack of such geographic information. Most planning agencies proceeded as best they could with the resources at hand, and there is a fair amount of inconsistency in the quality of the products.

Geoscientists and engineers were involved in classification and designation in many cities and counties, commonly as volunteer members of technical or citizens' advisory committees; they have also helped draft development regulations in some jurisdictions. Washington Department of Natural Resources geologists, librarians, and staff were among those who assisted with information and outreach. There are still many questions regarding who is going to create (and pay for) all of the reports and work still required, and to review all of the reports that will be generated.

Natural Resource Lands

The GMA directed that lands having commercially significant agricultural, forestry, and mineral resources are to be classified, designated, and conserved. The purpose of these provisions is to maintain the economic base of the state by considering in planning those lands that can be used for the commercial production or extraction of resource commodities. In this context, conservation means protection from conflicting activities that effectively prevent future resource use. In counties and cities that prepare comprehensive plans, the distribution of resource lands is supposed to influence the delineation of urban growth areas and other zoning decisions.

In the case of mineral resource lands, the intent was to ensure a future supply of mineral commodities, especially those necessary for urban development (sand, gravel, and stone), while maintaining a balance of land uses. Classification criteria include geologic, environmental, and economic factors. It is noteworthy that in some jurisdictions, the intent of the GMA seems to have been twisted: in their interim designations, some have restricted the mineral-resource designations to active mines, thus providing no immediate protection for potentially valuable deposits. The effect is to allow other uses that will ultimately preclude future use of the mineral deposits. This initial step may reflect the absence of reliable data on the probable location of commercial deposits, or local desires to prevent mining.

Natural Hazards and Critical Areas

Critical areas are to be classified, designated, and considered in planning in order to protect health, safety, and property by controlling land uses in areas that present some natural hazard or serve some important ecosystem function.

Geologic conditions and hazards are the result of a combination of factors. Physical processes, including tectonism (such as seismicity and volcanism) and climate (the hydrologic cycle and its many consequences), act on earth materials (rock, regolith, soil, and water) and landforms. They proceed in a particular historical sequence of events that control the specific distribution of materials and landscapes. In addition, human activities can trigger and accelerate natural hazards. These all interact with one another in a plexus of causes and effects.

In considering natural processes and hazards, many characteristics must be evaluated:

- *Magnitude:* Most natural process operate at a broad range of energy or amplitude. How powerful or damaging must an event be to qualify as a *hazard*?
- *Time:* The rate of occurrence of events. How rare or frequent are disastrous events of a particular type?
- *Effects:* The lives, structures, etc., that are vulnerable to a hazard event of a given magnitude. What is at risk?

- *Interactions:* Most serious geologic hazards have multiple effects. Could a great earthquake, for instance, trigger landslides, fires, floods from tsunamis or dam failures?

Evaluating the potential effects of hazard phenomena requires that we consider the interaction of processes and the elements at risk.

Hazard interpretations and predictions are based (as much as possible) on our collective experience with a natural process. For example, storms cause floods fairly often, and we can extrapolate from these relatively common events to future ones; we can imagine design floods, such as the 100-year event (the discharge with 1 percent probability each year). Other hazards occur less frequently. Large earthquakes are rare, yet from geology, seismology, and engineering we are figuring ways to develop "design earthquakes", on the basis of source mechanisms, magnitude, and local ground conditions, for input to planning, building codes, and construction. For very rare events, it is more difficult to make predictions. We now have some experience with the behavior of Cascade volcanoes, but it seems that each eruption is somewhat different. In any case, interpretations or predictions of geologic hazards for planning require consideration of events of interest, the model or design events that will be planned for. We ask, "What will happen *if* ________?", and then, "How should we *prepare* for that contingency?".

Spatial scale, the area likely to be affected, is another factor in hazard evaluation and planning. Some physical processes operate independently of terrain, whereas others act in fairly limited (and thus more predictable) tracts of land. For example, floods typically occur in low-lying areas near waterways; landslides are more likely on steeper slopes. Many types of geologic hazards are thus geographically *zonable* to some degree, and we can define areas where the damaging processes are more likely to occur.

Much effort in the study of geologic hazards is directed to the finer mapping of places subject to the hazards (that is, hazard zonation). Delineation of critical areas is aided by our ability to discriminate the places most at risk from particular processes. To a great extent, planning is a geographic exercise, and this is especially true for tasks such as preparing zoning maps and designating urban-growth boundaries. Maps of the zonable hazard areas are essential to making maps of critical areas for planning. Descriptions of a particular hazard area may be useful in determining whether a site belongs in a class, but a map is necessary for the geographic planning functions.

Information is vital to hazard evaluation. The procedure of making interpretations and predictions regarding geologic hazards involves a progression:

(1) *Description:* Hazard mitigation starts with recognizing that a hazard exists and understanding how it has operated in the past. *What you see is what you get.*

(2) *Interpretation:* Understanding the physical and human factors that affected the processes in the past provides information on how future events will occur. *The past is the key to the future.*

(3) *Prediction and forecasting:* Use of rational, mathematical, and probabilistic techniques helps to estimate the likelihood, magnitude, etc., of future events. *I model, therefore I predict.*

Likewise, the types of information available regarding natural conditions, materials, processes, and hazards can also be categorized by the degree of description or interpretation involved (Fig. 3). Descriptive-observational data generally are most available, but they require the greatest amount of expert interpretation for use in planning. Higher-order maps and information are easier to use, but interpretations for specific uses require much expert labor to produce (and therefore are rarely obtainable), and users must rely on the creators' methods and competence. Planners and decision-makers must be aware of the kinds of information they are using and realize that interpretive products may have to be specially generated.

Lastly, not all geologic hazards are created equal, and not all critical areas should be treated the same way in planning or restriction of development. Some hazards can be ameliorated by special design or emergency preparedness, but some cannot be economically mitigated and should be avoided. Accordingly, avoiding hazardous areas through zoning restrictions may be the best planning strategy in some cases, but lesser controls may be appropriate in others. The degree of a site's unsuitability for a particular use is partly determined by the way that the specific processes operate. At the extreme, for hazards that are so frequent or so potentially disastrous that avoidance is required, all residential, commercial, industrial, and institutional land uses could be prohibited and only low-intensity activities (such as open space or agriculture) allowed. With hazards that are less likely and (or) less destructive, the strategy might be avoidance for uses that are most sensitive to the hazard, and lighter restrictions on relatively robust uses, with provision for mitigation or special construction.

The delineation of the urban growth area should reflect these considerations. For hazard designations that are most uncertain or imprecise, the planning strategy might be first to require more information on the particular hazard in the proposal, so that site-specific mitigation can be required where necessary. In other words, land-use controls should be calibrated to the particular characteristics of the hazard and to the degree of hazard and risk in particular places. Geoscientists can help with these determinations.

LESSONS LEARNED

No planning process proceeds exactly the way we learned to do it in school. While the preferred path might proceed from inventory ⇒ analysis ⇒ choices and recommendations ⇒ final plan, commonly the necessary environmental information is incomplete or scattered. Instead, there are short-cuts because of time constraints, the lack of basic information, and fiscal limitations. In other words, it's not a completely rational or scientific process.

The planning mechanisms introduced by the Growth Management Act have been no exception. Major obstacles to the GMA process have emerged, and most of the original deadlines were extended. With respect to geologic hazards and resources, problems have included: misunderstanding of the requirements and guidelines; varied amounts and quality of relevant geologic information; inconsistencies intrinsic to geography, geologic processes and materials, and critical factors useful in evaluating hazards; inadequate funding for surveying geologic-hazard areas; and a lack of standards and institutional framework for evaluating geotechnical information.

Nevertheless, geoscientists had and will continue to have several roles in planning, within and outside the GMA process. Although the interim classification and designation of critical and resource lands are mostly complete, there will be revisions, corrections, and modifications as plans are written, development regulations are reviewed to ensure consistency with the plans, and annual amendments are considered. Geologists should stay involved with their cities and counties, particularly to supply new information (from continuing studies, mapping, measurement, and monitoring) that can be used to inform the amendment process. They will also be dealing with landowners and developers who must respond to the designations and the concomitant zoning and regulations. In this role, technical specialists will be evaluating the hazards and resources on particular sites (and addressing whether the designations are appropriate at that scale), providing information for architects, engineers, and builders to accommodate local geologic conditions and hazards. This should be an iterative process, with site-specific information cycled back into the urban and regional plans.

There are several different ways of evaluating geologic hazards: one by one, for each jurisdiction; by process (landslides, flooding, etc.), but as part of a regional hazards-evaluation program; for all geologic hazards in a county-size or multicounty region; or on a haphazard, site-by-site, project-by-project basis. In the early 1970s, attitudinal changes toward environmental protection and the resulting passage of new laws (SEPA, the Shorelines Management Act, the Forest Practices Act) drove the evolution of engineering and environmental geology and contributed to a surge of research in geologic hazards. This work has continued, but with a somewhat lower profile (and a lower funding level). Perhaps the Growth Management Act can stimulate new initiatives in the organized study of geologic hazards in Washington.

Although our participation in land-use planning is essential, experience suggests that earth scientists must be prepared to get involved early and often; to cross over into the realms of planning, engineering, and government; and to deal with situations and processes that are not as rational as those to which we are accustomed. This means we must inform ourselves about the perspectives and needs of other professionals (especially planners) and the public so that we can make ourselves understood by them. We must be prepared to make decisions without full study and complete information, and to continue to generate and incorporate new information into our plans and actions. We will have to review plans, proposals, and other documents, sometimes as volunteers and sometimes repeatedly, in order to be sure they turn out correctly. Likewise, planners must recognize the limits of available knowledge and become sufficiently informed to ask the appropriate questions of their technical advisors. Both groups must communicate to community leaders and citizens that our knowledge of geologic and hydrologic conditions relevant to land-use planning is uneven; and that, while we are prepared to make decisions based on incomplete information, we should also be willing to expend the funds needed to generate earth-science information that is useful for public planning.

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REFERENCES CITED

Bernkopf, R. L.; Brookshire, D. S.; Soller, D. R.; McKee, M. J.; Sutter, J. F.; Matti, J. C.; Campbell, R. H., 1993, Societal value of geologic maps: U.S. Geological Survey Circular 1111, 53 p.

Flawn, P. T., 1970, Environmental geology—Conservation, land-use planning, and resource management: Harper & Row, 313 p.

Galster, R. W., chairman, 1989, Engineering geology in Washington: Washington Division of Geology and Earth Resources Bulletin 78, 1234 p. (in 2 v.).

Howard, A. D.; Remson, Irwin, 1978, Geology in environmental planning: McGraw-Hill, 478 p.

Legget, R. F., 1973, Cities and geology: McGraw-Hill, 624 p.

Mathewson C. C.; Font, R. G., 1974, Geologic environment—Forgotten aspect in the land use planning process. *In* Ferguson, H. F., editor, Geologic mapping for environmental purposes: Geological Society of America Engineering Geology Case Histories 10, p. 23-28.

McGill, J. T., 1964, Growing importance of urban geology: U.S. Geological Survey Circular 487, 4 p.

McHarg, I. L., 1969, Design with nature: Natural History Press [for the American Museum of Natural History], 197 p.

Robinson, G. D.; Spieker, A. M., editors, 1978, "Nature to be commanded...."—Earth-science maps applied to land and water management: U.S. Geological Survey Professional Paper 950, 95 p. ■

Natural vs. Manmade Hazards

Casualties from specific geologic hazards compared with familiar societal hazards. We tend to think of geologic hazards, if we think of them at all, as being relatively mild. To put them in perspective with other disasters and hazards, see the table below. (Modified from Nuhfer, E. B.; Proctor, R. J.; Moser, P. H.; and others, 1993, The citizens' guide to geologic hazards: American Institute of Professional Geologists [Arvada, Colo.], 134 p.; used with permission of publisher.)

Causes of casualties	No. of casualties
Wars vs. earthquakes	
U.S. battle deaths in World War II	292,131
Atomic bomb, Hiroshima, Japan, 1945	80,000–200,000
Earthquake, Tangshan, China, 1976	242,000
U.S. murders vs. single volcanic eruption	
Total murders, U.S., 1990	20,045
Eruption, Nevado del Ruiz, Colombia, 1985	22,000
AIDS deaths in the U.S. vs. single landslide event	
Total AIDS deaths in U.S. through April, 1992	141,200
Landslides, Kansu, China, 1920	200,000
Greatest atrocity vs. greatest flood events	
The Holocaust, Europe, 1939–1945	6,000,000
Flood, Yellow River, China, 1887	900,000–6,000,000
Flood, Yangtze River, China, 1931	3,700,000

Mass Wasting on the Urban Fringe

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INTRODUCTION

Knowledge of the geology and geologic hazards of regions and land types plays a key role in land-use planning and management. Geologic information contributes to an understanding of ground-water conditions, earthquake hazards, site productivity, flood susceptibility, slope stability, and other conditions that give the landscape the shape and character we see and experience.

This article focuses on the slope-stability issues that arise at the interface between forest lands and those affected by urban and suburban growth (here referred to collectively as urban growth), primarily along the slopes of the Cascade, Olympic and coastal ranges in Washington. These urban fringes are experiencing some of the most rapid change in the state. The expansion of urban land uses into the surrounding farm and forest lands is fostered by population growth, improved transportation routes, and the desire of many people to live in a rural setting while still enjoying easy access to city jobs and amenities. Areas where urban growth and rural resource lands converge are sensitive to the costs and conflicts associated with population density increases. Consequently, society and state government are attempting to balance the pressures of urban growth and development with such goals as conservation of resource productivity, preservation of natural habitats and ecosystems, and protection from natural hazards.

Most of the lands between the steep forested upland slopes and the coastal cities and towns of western and central Washington—alluvial fans, broad flood plains, and rolling drift plains of the lowlands—have been used for activities such as farming, forestry, and recreation. But in many parts of the state, the urban fringe is moving into these areas, putting more people and property at risk from the effects of landslides from the steeper adjacent terrain. Avoidance and mitigation of such hazards depend on many kinds of actions, both private and governmental. Land-use planning agencies must recognize the susceptibility of lands considered for development to the combined processes of erosion and deposition, which sometimes occur catastrophically. Likewise, the owners and users of upland areas must become aware of the effects their activities could have on the growing numbers of people who live and work downhill and downstream.

The Growth Management Act (GMA) provides a set of procedures for evaluating geologic hazards relevant to development and accounting for them in the planning process. Furthermore, it mandates the classification and identification of these critical areas. The State Environmental Policy Act, the Shorelines Management Act, county and municipal critical-areas ordinances, and other laws and regulations have created other ways to evaluate geologic hazards. This article focuses specifically on forest management and the connections between forest-practices regulation and geologic hazards affecting nonforestry uses of adjacent lands. The examples presented here illustrate some of the potential problems caused by the interaction of landslide processes with forest operations around the urban fringe, and they suggest how information contributed by geologists for forest-practices regulation might be incorporated into growth-management planning and used to avoid such consequences.

SETTING

The physiography of the urban fringe/forest land interface in much of western and central Washington has been shaped by the interaction of many geologic processes, especially mountain-building and erosion. The tectonic and volcanic forces that built the Cascades, the Olympics, and coastal mountains are counteracted by glacial erosion, mass-wasting, and stream incision. The mix of high relief, a wet climate, and a history of recent glaciation has created terrain in which relatively flat lands, such as river valleys and drift plains, are adjacent to steep mountains or bluffs (Fig. 1). Many of these landforms are susceptible to hazards as a result of past and present geomorphic processes. (Later in this article, we discuss hazards resulting from or enhanced by human activities.)

The steep, commonly forested mountain slopes and bluffs are prone to various forms of mass wasting ranging from shallow debris slides, to large deep-seated slump-earthflows, to far-reaching and dangerous debris torrents (Sidle and others, 1985; Eisbacher and Clague, 1984; Thorsen, 1989a), all of which can affect otherwise relatively flat and stable lands nearby and their occupants. In the urban fringe setting, many of the landforms are the result of the repeated occurrence over long periods of time of landslides or debris torrents that start on adjacent slopes, travel down incised drainages, and deposit large loads of debris on their fans (Fig. 1).

Although these are natural processes, many studies suggest that certain human land-use activities are increasing the rate and possibly severity at which such events occur (Sidle and others, 1985). Forest practices, particularly timber harvest and road construction, are among the activities that can initiate mass wasting, especially in unstable or marginally stable terrain (Fiksdal and Brunengo, 1980, 1981; Ice, 1985; Pentec Environmental, 1989). Road construction rearranges the materials and water movement on a slope; harvest of trees and subsequent decay of their roots reduces the strength contributed to the soil by those roots; soils are often exposed and damaged during yarding of logs, further disrupting the soil-vegetation mat on a slope. Even small landslides can contribute large amounts of soil, rock, and organic debris to stream channels. In the worst cases, they can initiate destructive debris torrents, which can move at high velocity and expand in volume by incorporating channel sediment and debris (known as "bulking"). Midslope failures in the upper reaches of drainage basins, such as those in the Sygitowicz Creek drainage

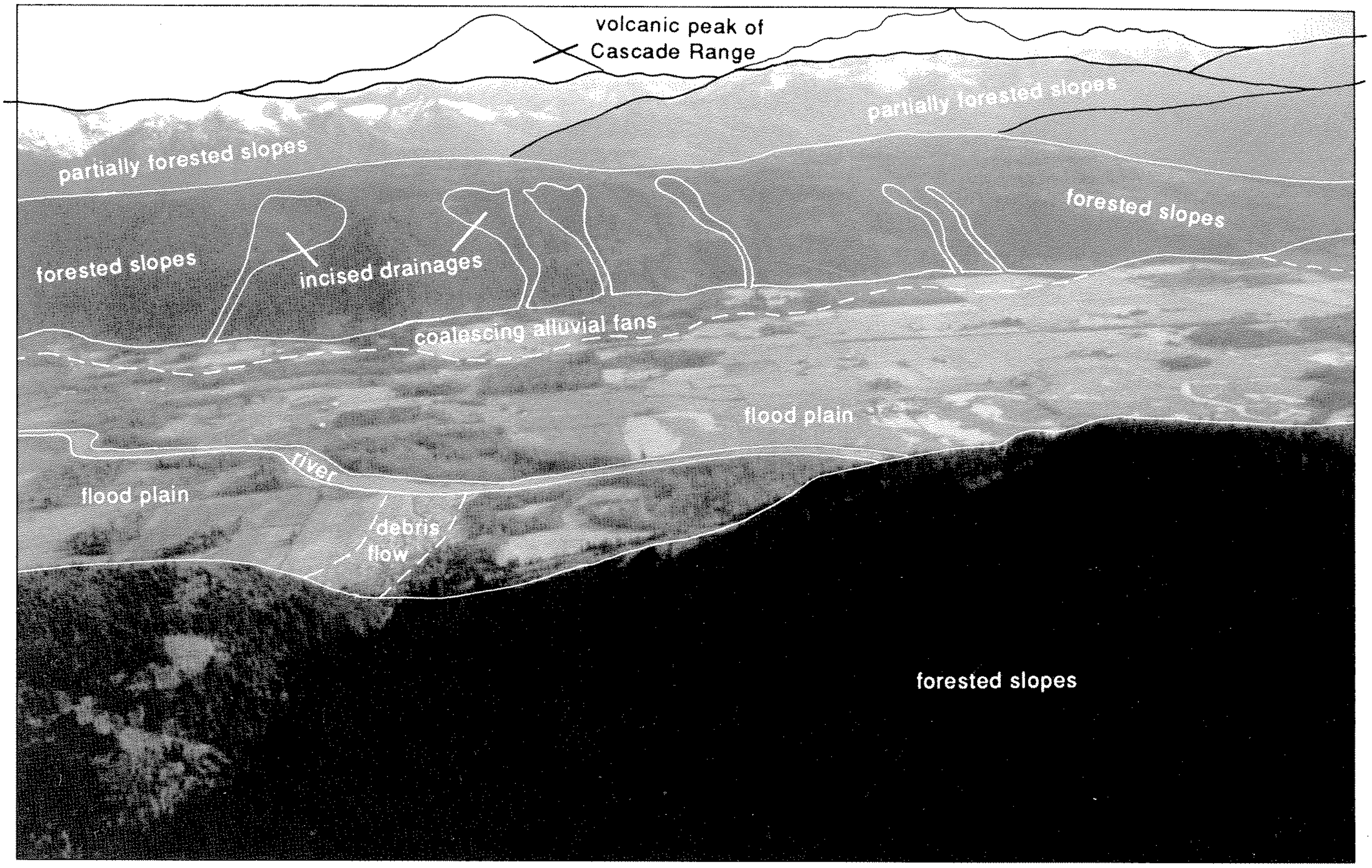

Figure 1. Oblique aerial photo showing major geomorphic features discussed in this paper. View east toward Mount Baker from a position over Sygitowicz Creek across the valley of the South Fork Nooksack River.

(Fig. 2), also contribute material to debris flows (Dragovich and others, 1993a,b).

EXAMPLE 1: JANUARY 1983 STORM, WHATCOM AND SKAGIT COUNTIES

Debris torrents have been responsible for at least five deaths and much destruction in Washington over the past several decades (Logan, 1989). This 1983 example illustrates some consequences of landslides initiated on naturally unstable slopes and in steep drainages, combined with the failure of unmaintained forest roads and the movement of accumulated logging slash and debris.

Issues regarding natural versus logging-induced mass movements were raised on the morning of January 10, 1983. Following a week of heavy rain, an unusually intense and stationary downpour delivered between 5 and 8 inches (enhanced by snowmelt) over about 10 hours, triggering debris torrents in at least 22 drainages in western Whatcom and Skagit Counties (Fig. 3). In the hills around Lake Whatcom, the areas underlain by the Chuckanut Formation (Eocene fluvial sandstones, siltstones, conglomerates, and coal) experienced many small debris slides (and a few large ones) in immature and mature timber stands and even ancient forests. Failures of old and abandoned road and railroad fills were es-

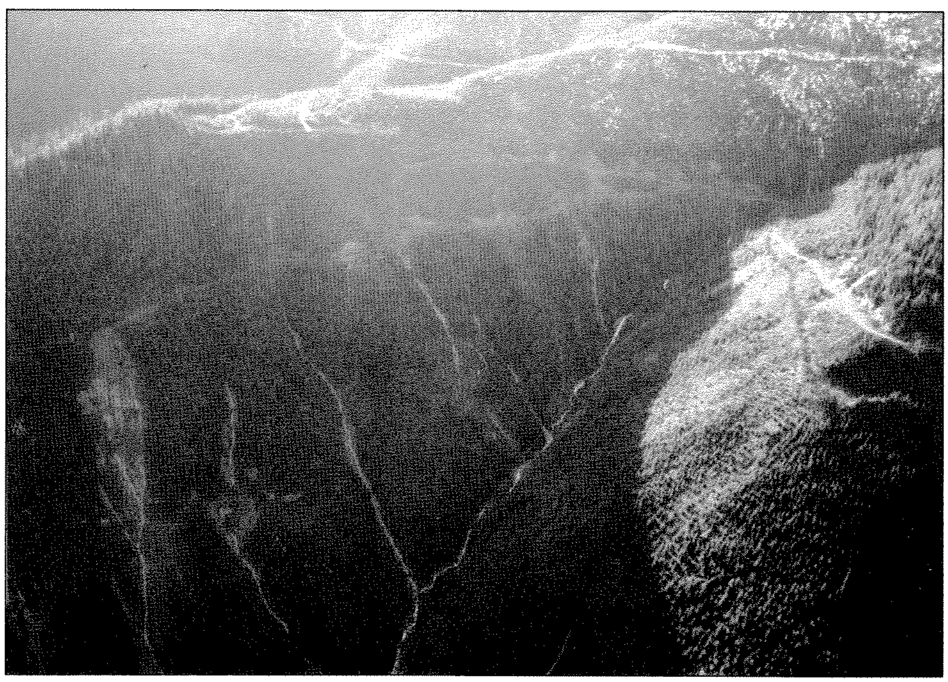

Figure 2. Sygitowicz Creek drainage, Whatcom County. Note the many shallow midslope debris slides that contributed to debris torrents in the main channel. Similar processes occurred in several other drainages during the January 1983 storm. (Photo by Rolli Geppert.)

pecially common. In areas underlain by Darrington Phyllite, a metamorphic rock that is more susceptible to slow earthflow (Thorsen, 1989b), the numbers of landslides were much smaller, but a few road-fill failures triggered debris torrents. The torrents, charged with large loads of logs and other organic debris, moved rapidly from the mountain channels onto the deltas around Lake Whatcom and onto terraces and flood plains of the Nooksack, Samish, and Skagit Rivers (Fig. 3) (Buchanan and Savigny, 1990.)

In addition to one death and several injuries, the Federal Emergency Management Agency reported documented damage to more than 300 houses and barns, among them at least 34 houses heavily damaged or destroyed. Initial damage estimates topped $14 million, and $1.5 million was spent on clean-up in the two weeks after the event. Debris torrents washed out county, private, and logging roads, bridges, and culverts; delivered tons of logs and slash to pastures, lawns, and waterways (especially Lake Whatcom); and broke or plugged sewers, storm drains, and water lines. Considering that most of the torrents occurred in predawn darkness (at about 4:30–6:00 a.m.), it is fortunate that the number of deaths and injuries was not greater.

One such debris torrent discharged onto the alluvial fan at the mouth of Mills Creek, on the west side of Lyman Hill (Fig. 4). The mass of mud and logs carried by the torrent was responsible for the death of one man (several other people escaped) and about 200 veal calves and the destruction of several farm buildings located on the fan. In addition to the loss of human and animal life and the agricultural resource of about 30 acres of pasture buried by sediment, consequences of the debris torrent extended downstream. The phyllite and overlying till contributed large amounts of fine material to the debris torrent and resulted in sedimentation of the Samish River, into which Mills Creek flows, with some impact on fish habitat. Mud from the torrent runout temporarily disrupted activity on the railroad that traverses the fan and damaged or destroyed irrigation channels (which fed more fine sediment into the Samish River) and access roads to the farms on the east side of the valley. There are also power lines and a pipeline crossing the base of the fan; none of these was damaged, however.

The Mills Creek debris torrent and its impacts were the subject of one of several lawsuits that resulted from the 1983 storm. Subsequent investigations by geologists, geomorphologists, and other specialists attempted to determine the causes and chronology of the many torrents. Apparently the 1983 Mills Creek debris flow had been initiated by the failure of a large fill from an abandoned road. The road crossed an old earthflow, which evidently moved during the event: either the road-fill failed, destabilizing the landslide, or the slide moved, pushing the fill into the channel. Regardless, the road material moved into the tributary stream, which was flowing vigorously at the time. The slurry became a debris flow which bulked its volume by scouring the channel and lower slopes, incorporating organic debris (including logging slash) and alluvial material on its way downstream. In January 1984, another storm caused a fill failure on the newer road uphill, which triggered a

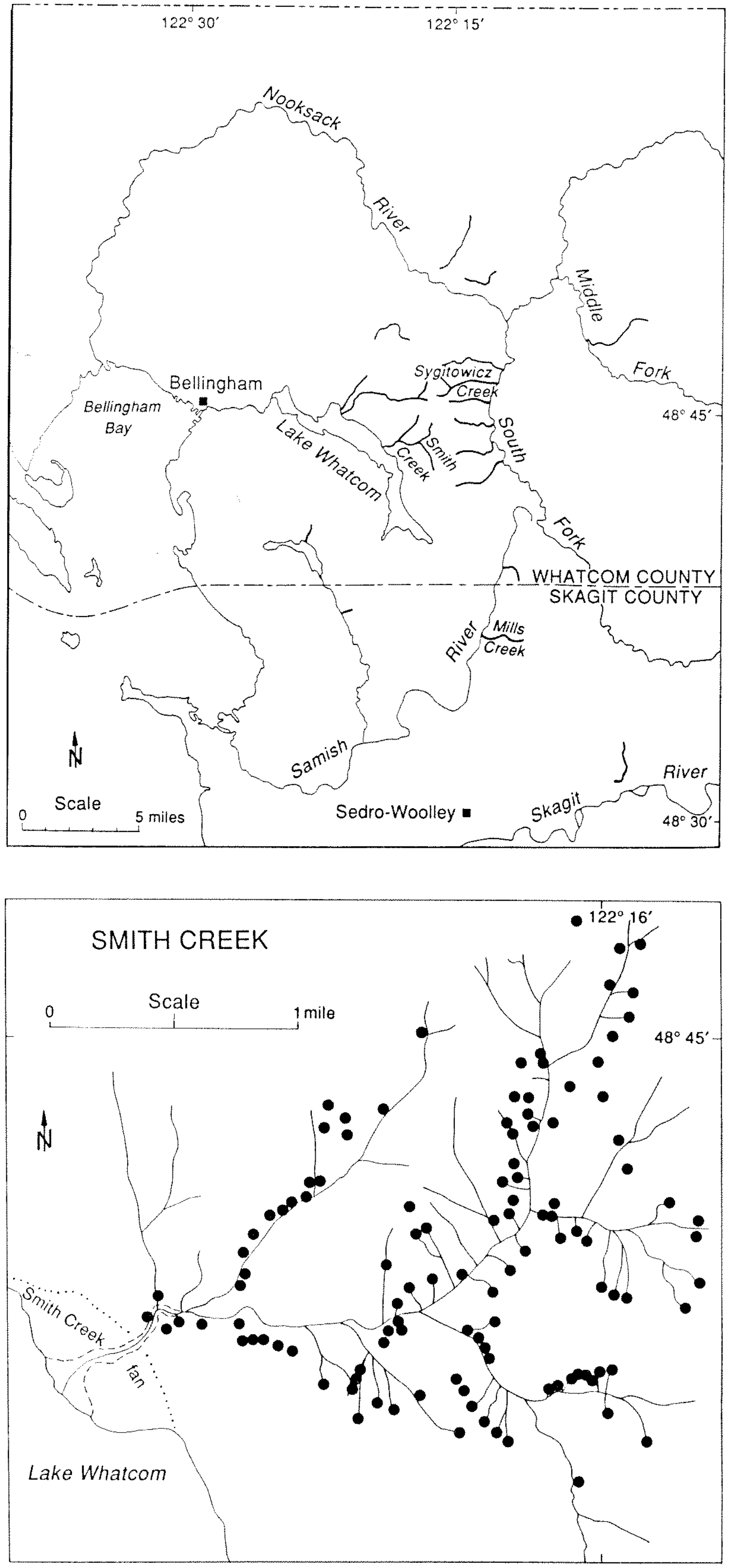

Figure 3. Drainages in Whatcom and Skagit Counties (top) that were affected by debris torrents during and following the unusually high precipitation of January 1983. Note the locations of Smith, Mills, and Sygitowicz Creeks, discussed in the text. In the Smith Creek drainage (bottom), locations of debris torrents, debris avalanches, and other areas of mass-wasting resulting from the January 1983 storm events are shown. Similar mass wasting took place in other tributary drainage basins for the rivers shown in the top figure.

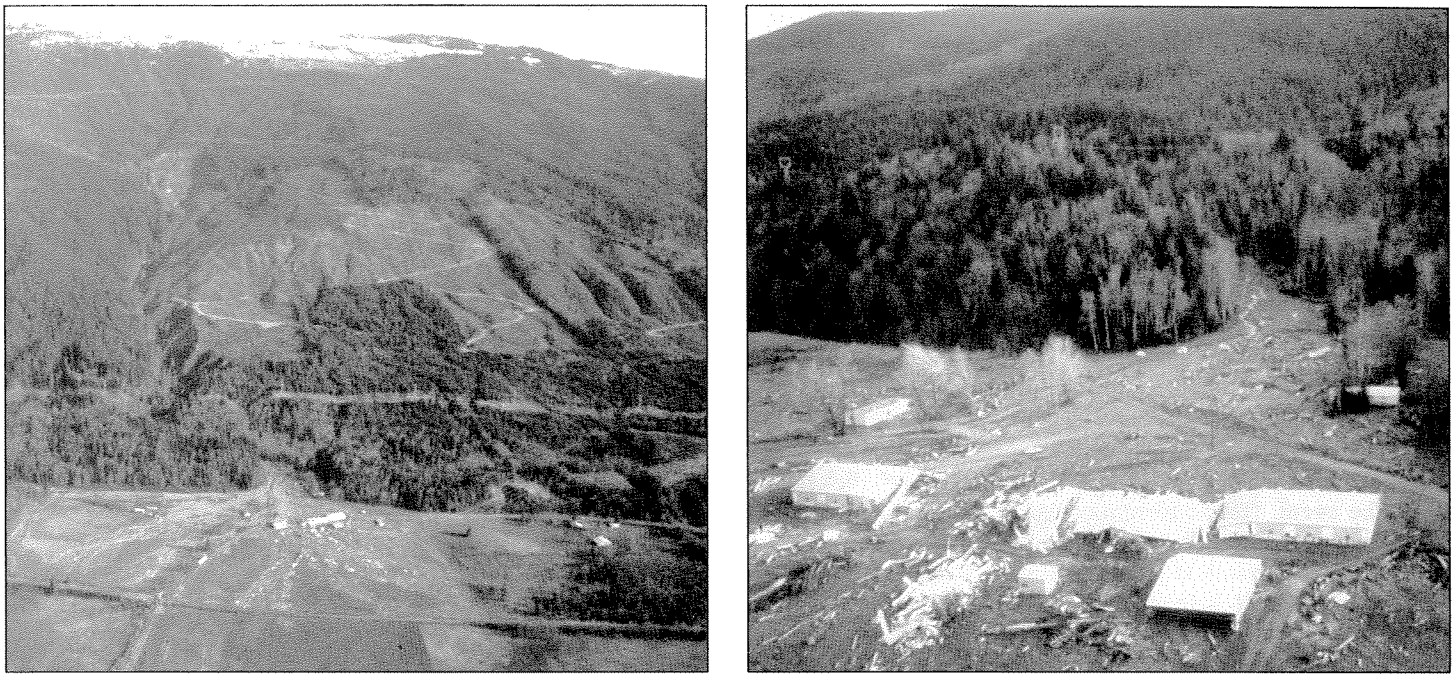

Figure 4. Oblique aerial photos of Mills Creek fan and the farm damaged in the 1983 debris flow, which resulted in the death of one person and more than 200 veal calves. The photo on the right is a closer view of the farm shown at the head of the fan in the left photo.

second debris torrent in the same tributary; the results were similar in type but with less severe consequences.

Alluvial fans, such as the one at the mouth of Mills Creek, are identified in the geologic and geomorphic literature as potentially hazardous sites, although their susceptibility to hazards had not been emphasized (or sufficiently communicated to the public) as much in the Pacific Northwest as in other regions. Some of the fans had experienced similar events in the recent past: damaging torrents (apparently muddy floods from log debris-jam failures) had occurred on the Smith Creek fan in 1917, 1949, and 1971 (with one fatality in 1917). And yet, people continued to build homes, farm structures, and other facilities on the fans. The areas around Lake Whatcom were especially subject to increasing development moving out from Bellingham. Along the flood plains of the Nooksack and Samish Rivers, the fans seemed like logical places for farm buildings because they provided gently sloping ground that was high enough to be protected from flooding. The small creeks flowing out of the mountains supplied water to the early settlers and became amenities to the later residents. Even given the history of debris torrents (commonly considered just floods), there was little public or governmental recognition of the risk. To the extent that they were required, building permits were issued to the landowners by the counties with (apparently) no consideration of the hazard of debris flows in such areas.

THE ROLE OF THE GEOLOGIST

The Forest Practices Act (FPA) and its associated regulations and procedures provide several means of gathering information on the stability of forested slopes within and around the urban fringe. The law and regulations mandate that public resources (streams, wildlife, public capital improvements, and public safety) are to be protected from significant harm during the conduct of forest practices, and they set up procedures for the DNR to follow in processing permit applications. Consideration of slope instability with regard to roads was in the original rules; subsequent revisions have expanded coverage to stability issues surrounding timber harvest. Either road construction or harvest on slide-prone slopes now results in review under the State Environmental Policy Act. The Timber/Fish/Wildlife (T/F/W) Agreement of 1987, in which state agencies, Native American tribes, the timber industry, and environmental groups agreed to pursue cooperative means of forest management and regulation, led to more site-specific, field-oriented procedures of problem recognition and resolution.

In particular, the T/F/W Agreement promoted the use of interdisciplinary (ID) teams during the processing of applications to examine the potential for damaging effects. An ID team consists of a group of people having special expertise in geology, geomorphology, soils, hydrology, fish and wildlife biology, and forest engineering assembled at a site to respond to the technical questions associated with a proposed forest practice activity. When previous experience, reconnaissance of a site, or other information (from review of technical literature, geologic maps, or soil-stability ratings) suggest the potential for mass wasting, soil erosion, or stream sedimentation, the regional DNR regulatory forester will generally convene an ID team to evaluate and mitigate those potential effects. The downstream and downslope effects of the potential geologic hazards are also addressed during the ID team meeting. As participants on ID teams, geologists investigate and make recommendations for maintaining the stability of the site based on the nature of the geologic materials and structures, soils, slope gradients, slope aspect, elevation, vegetation, and historical evidence of geomorphic processes.

Classifying and identifying geologically hazardous areas, in this case potentially unstable forest slopes and soils and associated areas of deposition, require knowledge of geomorphic and hydrologic processes. Furthermore, ID team participation requires some understanding of logging systems and road-building techniques to be able to coordinate efforts with other specialists to prevent, control, or mitigate identified site problems.

The Office Investigation Process

Before going into the field with an ID team, the geologist reviews historic records such as previous reports, aerial photos, geologic and geomorphic maps at various scales, state and county soil surveys, and well logs or any other subsurface information (if available). Map overlays are commonly made of the site and its surroundings to delineate landslide-prone areas, surface erosion features, wetlands, and other critical areas. The overlays can also show potential sediment-delivery routes to streams, existing and potential road and (or) culvert failures, and other known or potential drainage problems.

The geologist uses this information to plan the field visit, developing an understanding of site conditions and potential effects of proposed activity. Evidence of historic instability generally implies conditions for continuing geologic hazard. Types of features noted on maps and aerial photos by the geologist include eroding cliffs and bluffs, existing landslide scars, large slump-earthflows, unstable soils, and areas underlain or covered by mass-wasting debris, such as talus slopes and alluvial fans. But the geologist also looks for combinations of conditions that can suggest possible future movement: steep slopes, cohesionless soils over bedrock, weak or shattered bedrock, favorable bedding or joint orientations, or ground-water seepage.

The Field Investigation Process

At the site, results of office work are verified or re-evaluated as necessary. On-site assessment of slope-stability conditions continues by identification of local rock types, structures, alteration and weathering characteristics, jointing, permeability, erodibility, fracturing, slope gradients, aspect, rooting depth of large and small vegetation, location of seeps, jackstrawed trees, and any other relevant factors. (A jackstrawed tree is one that has continued to grow as its basal area tilts due to slope movement, resulting in a concave upward, or J shape of the trunk.)

Combined, these conditions can indicate the relative strength of the forces favoring or resisting slope movement. For a proposed timber harvest, they can help the geologist understand the possible effects of removing the forest cover (Greenway, 1987; Dragovich and others, 1993a,b). In the case of road construction, the effects of rearranging natural drainage pathways and soil and rock on a slope can be predicted to some extent from the characteristics of the site.

A discussion of rock-slope mechanics and the potential for blocks of rock to fail at the intersection of joint planes is beyond the scope of this article. However, rock characteristics also play an important role in road failures and the production of fine sediment that can subsequently be transported downslope and into streams (Swanson and Grant, 1982; Burroughs and King, 1989). Material used in road construction, combined with seasonal variations in precipitation, temperature, and traffic, have a notable effect on road prism stability and the erodibility of surfacing materials.

As indicated earlier, a site assessment must also include an evaluation of the local hydrologic conditions. Studies have shown that disruption of the natural drainage patterns by inadequate or poorly located culverts is a cause of slope failure. Research also suggests that canopy removal can increase peak-flow magnitude and frequency and influence the rate of slope failures (Harr, 1981, 1986).

The results of each site investigation are generally documented in field notes and a final report submitted to the regulatory forester. This written documentation of site conditions and recommendations becomes part of the public record. These reports could be useful to planners.

EXAMPLE 2: DAVIS TERRACE, KELSO, WASHINGTON

An application for timber harvest on an existing large, slow-moving landslide prompted a request for an ID team to review the proposed logging activities. Of additional concern was the probable subsequent residential development of the site. This example illustrates the workings of an ID team, as well as the local and far-reaching effects that geologic characteristics of a site, in both its natural and disturbed conditions, can have on long- and short-term slope stability and land use.

Davis Terrace overlooks the Columbia River just southeast of Kelso. It is underlain by poorly consolidated gravels and sands of the Troutdale Formation (Pliocene–Quaternary), which here overlie Eocene siltstones, sandstones, and shales of the Cowlitz Formation (Phillips, 1987). The contact between the two generally westward-dipping units is a boundary across which permeability changes and that tends to collect and perch water, thereby providing a slip surface for the overlying material.

Davis Terrace has a history of slope movement evident in the aerial photos and sketch overlay in Figure 5. (See also Fiksdal, 1973.) These photos reveal a stepped sequence of benches on the west-facing slope that suggest a series of rotational slumps. Both the old and the reconstructed locations of Interstate Highway 5 are also visible in the aerial photo. I-5 was rerouted in the late 1970s from the base of the slope (the route inherited from U.S. Highway 99) westward across the Coweeman River and into the valley because of continual downslope movement of the road prism and periodic failure of the hillslope onto the road. Reconstruction of the by-passed road section consisted of riprapping the cutslope along the northbound lanes.

The proposed timber harvest was to occur on the lower benches, within approximately 150 feet of the old highway. During the field visit the ID team noted many features common to active rotational slumping. For example, trees rooted on the bench surfaces tilted back toward the hillside, while many on the scarp or outer slopes leaned outward, away from the slope. The oversteepened outside edge of the slump blocks revealed disturbed root systems and subsequent surface failures. One slump block was located directly above a home (Fig. 5, location A). At the base of some of the headwalls, on the back-tilted bench surfaces, are small areas of ponded water and (or) evidence of periodic ponding of intermittent streams. Disruption of stream channels by previous logging had rerouted and dispersed some flow. A prominent creek on the property dispersed water and sediment (fine sand, silt and clay) onto a fan at the base of the slope, covering a large area behind some nearby homes.

The ID team members had several concerns with the proposed logging plan. They recommended leaving some trees on the oversteepened upper slump-block slopes to maintain root strength and thereby help preserve the stability of the slope; all trees were to be left on the slump-block slope above the home at location A (Fig. 5). The team also recommended that trees adjacent to the larger stream channels should be left to provide channel bank stability and to help recruit large woody debris for trapping sediment. Additional recommendations included leaving trees on the headwall and scarp areas to reduce the risk of increasing surface erosion and instability on isolated portions of the large landslide. Harvesting in those areas would risk not only affecting these localized unstable areas, but also increasing the rate of downslope movement of the large landslide.

Despite the efforts that go into these site investigations, there is no guarantee that the outcome will be as recommended by the ID team members. First, the DNR regulatory forester must consider the team's recommendations, but approval and conditioning decisions are commonly made in the context of competing technical, legal, economic, and political factors. Second, although an increasing amount of attention is being paid to compliance, the DNR generally has to rely on the land owner and (or) operator to follow the conditions and best management practices necessary to protect the resources in question. In most instances the system works, but there are some problems. In the Davis Terrace case, trees were cut from the steep slope behind the home at the base of the lowermost slump block, in violation of the conditions on the permit. The owner was cited and fined for noncompliance and required to remove the cut trees carefully to avoid further disturbance of the soils and overland flow of water.

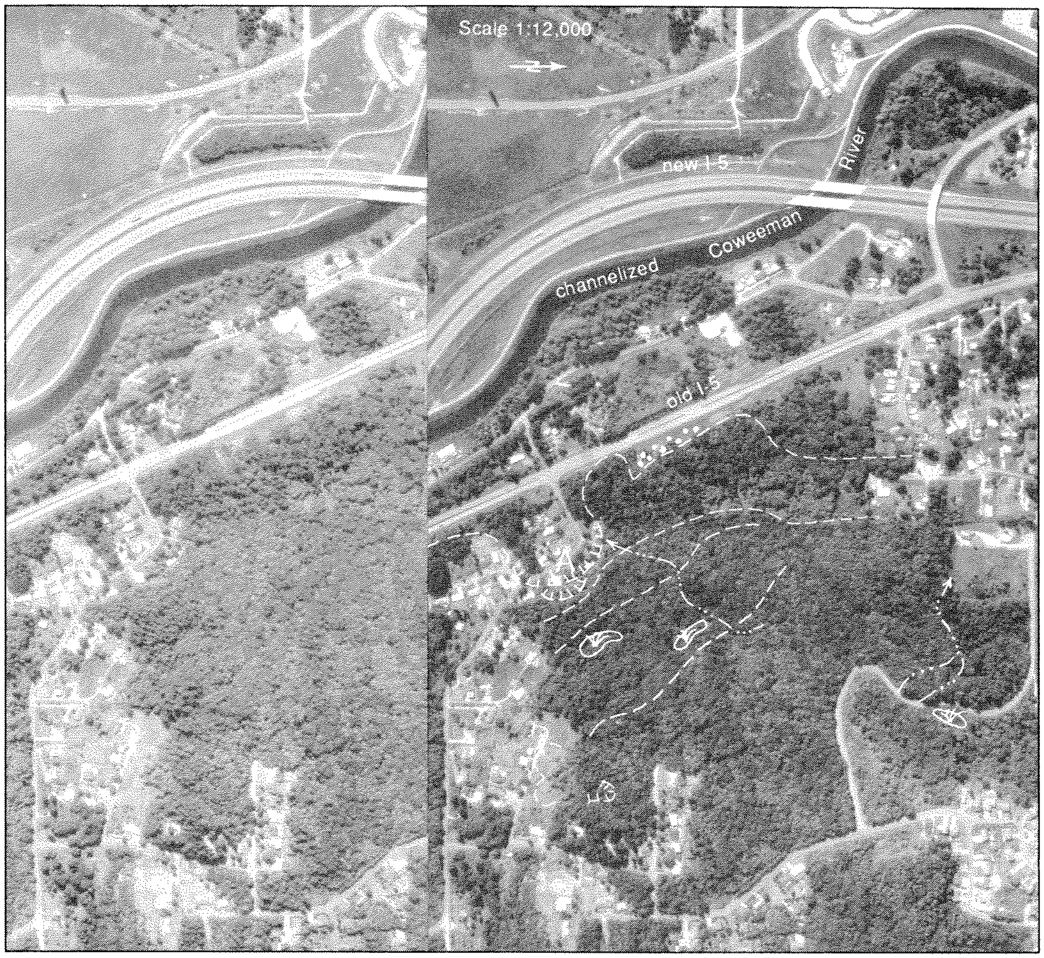

Figure 5. Stereophoto pair of Davis Terrace site. Note the sequence of slump blocks that make up a large earthflow, the toe of which abuts old U.S. Highway 99. Disturbed vegetation and drainage are visible. The house mentioned in the text as being at the base of the lower slump block is at A.

The Davis Terrace site illustrates the effects of a particular geologic hazard on its underlying and adjacent area. This example shows that human activities, superimposed on a site that has both small- and large-scale geologic hazards can have potentially far-reaching effects—financially (taxes covering road repairs), in time (immediate and long-term instability), and spatially (local residents as well as interstate travelers). It demonstrates that slope-stability issues should be addressed on a variety of scales in both long and short time frames. But it also shows how earth scientists, working in the context of forest-practices regulation, can conduct a site investigation that can help prevent or ameliorate forest slope-stability problems, which could affect lives and property in urban lands.

CONCLUSIONS

Both examples presented in this article illustrate that the potential effects of geologic processes and human land uses in adjacent areas have frequently not been fully integrated into the scope of a particular investigation. Some site studies for forest practices do not adequately consider potential effects on nonforest lands downhill and downstream, and planning inquiries and procedures may not give sufficient thought to the possibilities of hazardous conditions that might exist (or be created) in the surrounding mountains. In addition, the documentation of site assessments is not typically transferred from the forestry organizations to local planners.

These oversights are being corrected as a result of changes in both forest practices and planning regulations. In forest practices, site-related investigations of ID teams are now being supplemented by basin-scale examinations under the new watershed analysis program. Both can provide information that is relevant to development in the urban fringe. In planning, the GMA requires the identification, documentation, and protection of geologically hazardous areas, providing a process for incorporating the information into the planning system. With the implementation of the GMA, counties now have clearer authority to protect citizens by designating hazardous areas: by requiring site investigations in such areas, and by granting or refusing building permits on the basis of information from such site investigations.

The examples presented in this article illustrate that negative effects of poor land-use planning and inadequate forest practices can range from mere inconvenience to catastrophic property destruction and loss of life. These negative consequences are highlighted here because they tend to be the most noteworthy and are the ones that prompt us to revise and improve our standards of management. There are numerous examples of sound planning and management that have resulted in productive forest use and (in recent years) improvements in fish and wildlife habitat.

The lesson we are learning is that we need to understand, evaluate, and monitor natural systems holistically and cumulatively. The GMA and FPA are forcing us to do that. In a departure from earlier management ideology, scientists and society as a whole are recognizing the need to manage for entire watersheds and beyond, rather than exclusively on a site-specific basis. As scientists, we need to improve the transfer of investigative findings to planning agencies and the public. Updated information and revised standards of management should be used to amend existing comprehensive plans and zoning regulations. Mandates of the GMA, in combination with our developing understanding of watershed and habitat systems, will encourage the incorporation of revised standards and continuing geologic-hazards mapping into local and regional planning programs.

REFERENCES CITED

Buchanan, P.; Savigny, K. W., 1990, Factors controlling debris avalanche initiation: Canadian Geotechnical Journal, v. 27, no. 5, p. 659-675.

Burroughs, E. R.; King, J. G., 1989, Reduction of soil erosion on forest roads: U.S. Forest Service General Technical Report INT-264, 21 p.

Dragovich, J. D.; Brunengo, M. J.; Gerstel, W. J., 1993a, Landslide inventory and analysis of the Tilton Creek–Mineral River [sic] area, Lewis County, Washington; Part 1. Terrain and geologic factors: Washington Geology, v. 21, no. 3, p. 9-18.

Dragovich, J. D.; Brunengo, M. J.; Gerstel, W. J., 1993b, Landslide inventory and analysis of the Tilton River–Mineral Creek area, Lewis County, Washington; Part 2. Soils, harvest age, and conclusions: Washington Geology, v. 21, no. 4, p. 18-30.

Eisbacher, G. H.; Clague, J. J., 1984, Destructive mass movements in high mountains—Hazard and management: Geological Survey of Canada Paper 84-16, 230 p.

Fiksdal, A. J., 1973, Slope stability of the Longview–Kelso urban area, Cowlitz County: Washington Division of Geology and Earth Resources Open File Report 73-2, 4 p., 2 pl., scale 1:24,000.

Fiksdal, A. J.; Brunengo, M. J., 1980, Forest Slope Stability Project, Phase I: Washington Department of Ecology Technical Report 80-2a, 18 p., 7 pl., scale 1:250,000.

Fiksdal, A. J.; Brunengo, M. J., 1981, Forest Slope Stability Project, Phase II: Washington Department of Ecology Technical Report 81-14, 2 v.

Greenway, D. R., 1987, Vegetation and slope stability. *In* Anderson, M. G.; Richards, K. S., editors, Slope stability—Geotechnical engineering and geomorphology: John Wiley, p. 187-230.

Harr, R. D., 1981, Some characteristics and consequences of snowmelt during rainfall in western Oregon: Journal of Hydrology, v. 53, no. 3-4, p. 277-304.

Harr, R. D., 1986, Effects of clearcutting on rain-on-snow runoff in western Oregon—A new look at old studies: Water Resources Research, v. 22, no. 7, p. 1095-1100.

Ice, G. G., 1984, Catalog of landslide inventories for the Northwest: National Council for Air and Stream Improvement (NCASI) Technical Bulletin 456, 78 p., appendices.

Logan, R. L.,1989, Slope stability and rural land management—The Marblemount landslide case history. *In* Galster, R. W., chairman, Engineering geology in Washington: Washington Division of Geology and Earth Resources Bulletin 78, v. II, p. 903-910.

Pentec Environmental, Inc., 1991, Methods for testing the effectiveness of Washington forest practices rules and regulations with regard to sediment and turbidity; Report for Project 059-001: [Submitted to] Washington Department of Natural Resources, 100 p.

Phillips, W. M., compiler, 1987, Geologic map of the Mount St. Helens quadrangle, Washington and Oregon: Washington Division of Geology and Earth Resources Open File Report 87-4, 59 p., 1 pl., scale 1:100,000.

Prellwitz, R. W.; Koler, T. E.; Steward, J. E., and others [in press], Slope stability reference guide for national forests in the United States: U.S. Forest Service Engineering Management Report EM-[0000]-94, 3 v., 985 p., appendices.

Sidle, R. C.; Pearce, A. J.; O'Loughlin, C. L., 1985, Hillslope stability and land use: American Geophysical Union Water Resources Monograph 11, 140 p.

Swanson, F. J.; Grant, G., 1982, Rates of soil erosion by surface and mass erosion processes in the Willamette National Forest: U.S. Forest Service Pacific Northwest Research Station Report, 50 p.

Thorsen, G. W., 1989a, Landslide provinces in Washington. *In* Galster, R. W., chairman, Engineering geology in Washington: Washington Division of Geology and Earth Washington Bulletin 78, v. I, p. 71-89.

Thorsen, G. W., 1989b, Splitting and sagging mountains: Washington Geologic Newsletter, v. 17, no. 4, p. 3-13. ■

Association Executive to Retire

Karl W. Mote, executive director and vice president of Northwest Mining Association, has announced his retirement at the end of 1994. He has held the position since January of 1976.

Mote's career began with the degree of metallurgical engineer from the Colorado School of Mines in 1949. He worked at several locations for U.S. Steel, first in production and then in exploration and raw materials shipping. He worked for Gulf Resources' Vanguard Exploration in Spokane, NL Industries Exploration in Golden, CO, and St. Joe Exploration in Toronto prior to accepting the Northwest Mining Association position. He holds membership in several professional societies and is a registered professional engineer.

The association grew to a membership of 3,000 in the mid-1980s and has over 2,700 members today, enjoying a reputation as a supportive voice for mining. Founded in 1895, it is one of the oldest continuing mining trade associations. Its charter includes Alaska, British Columbia, Alberta, Yukon, the Northwest Territories, Washington, Oregon, Idaho, and Montana. Its headquarters has always been in Spokane, WA.

The change in leadership will take place at the centennial meeting in Spokane, November 30 to December 2.

Geologic and Geophysical Mapping of the Spokane Aquifer—Relevance to Growth Management

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INTRODUCTION

Rapid population growth in the Spokane Valley is taxing the natural filtering capacity of its aquifer. Studies have shown that water quality is already deteriorating at the margins of the aquifer (Drost and Seitz, 1978; Dion, 1987; Hall, 1991). As more pollutants are put into the aquifer by septic tanks, industrial chemical waste, storm water, and other sources, the positive effects of dilution are minimized. The water table is also likely to become lower with the increase in population and rates of water withdrawal. Without adequate information about water flow directions, volumes, and velocities, our calculations for tolerable septic densities, water availability, and dispersion of pollutants will not accurately represent conditions of the Spokane Valley Aquifer.

The Division of Geology and Earth Resources (DGER) of the Washington Department of Natural Resources (DNR) is under contract to Spokane County to gather and compile detailed information about the surface and subsurface geology of the Spokane Valley Aquifer, the portion of the Spokane Valley–Rathdrum Prairie Aquifer that lies in Washington State (Fig. 1). Some information from Rathdrum Prairie, the portion of the aquifer lying in Idaho, is also being incorporated into the study. The new information will provide hydrologists with a much-improved representation of the size and shape of the aquifer. This will allow them to generate a more accurate model of ground-water flow westward through the Spokane Valley. The results of the aquifer modeling will, in turn, offer city and county planners much needed information about the capacity of the aquifer to sustain a growing population. This work is being funded by a grant from the U.S. Environmental Protection Agency (EPA) and administered through Spokane County.

Project work began during the spring of 1992 and will continue for at least the rest of 1994. State and private geologists and geophysicists are collaborating on this project. Products being prepared for the county by DGER and SeisPulse Development Corp. include maps of surficial geology at a scale of 1:24,000, seismic reflection profiles, and geologic cross sections constructed from water-well data and the seismic-reflection data. An additional goal is to produce an improved three-dimensional representation of the configuration of the aquifer from these data.

REGULATORY BACKGROUND AND PREVIOUS WORK

In 1978, the Spokane Valley Aquifer was designated by the EPA as a sole-source aquifer under the provisions set forth in 1974 by the Safe Drinking Water Act. The Spokane Valley Aquifer is the major source of drinking water for approximately 350,000 people living in the Spokane Valley area, affirming the appropriateness of the designation. The designation requires that EPA review programs that are financially assisted by the federal government to assure that aquifer quality is not degraded and to prevent significant hazard to public health. Furthermore, under the mandates of Washington's Growth Management Act (GMA) of 1990 (and amended in 1991), the county must delineate the Critical Aquifer Recharge Area (CARA) and plan for appropriate land use within its boundary. The Aquifer Sensitive Area delineated by Spokane County (Fig. 1) generally fits the definition of a CARA and incorporates areas in which contaminant discharges could affect ground water. All activities and land and water use within this boundary must comply with specific ordinances established by the city and county.

In order to protect this designated sole-source aquifer, sources of pollution, such as septic tank seepage, storm-water runoff, and industrial waste, must be located and mitigated. Large databases are already available that can contribute to and facilitate growth management planning. A Geographic Information System-based contaminant source inventory was developed for the Aquifer Sensitive Area (Lackaff and others, 1993) for a Spokane Wellhead Protection Program. These data can be used to identify existing areas of high contaminant concentrations, to locate industrial and private landowners not in compliance with local standards, and to define zones of lower risk for future industrial and (or) residential development. Furthermore, the data provide geologists with additional information about subsurface geologic and hydrologic conditions that can be fed back into the planning loop.

Several studies, using a variety of models and equations, have resulted in estimations of ground-water flow in the Spokane Aquifer ranging from 500 to more than 1,000 cubic feet per second. The study by Bolke and Vaccaro (1981) used a digital computer model to predict the effects of increased pumping on aquifer heads and streamflow. They based their approximations of the aquifer shape and depth-to-bedrock on a combination of information sources that included bedrock mapping (Weis, 1968), water-well logs (only a few of which penetrate bedrock along the margins of the basin), seismic refraction profiling (one line just north of Spokane and one along the Washington–Idaho border; Newcomb and others, 1953), and gravity mapping (Purves, 1969). Bedrock configuration in the valley was inferred by projecting bedrock/alluvium contacts from valley margins downward and by using estimates of aquifer thickness from the limited water-well log, seismic, and gravity data. The depth-to-bedrock approximations were incorporated into a hydrologic model to yield estimates of ground-water flow. This produced simple models of the configuration and total thickness of the valley fill and, thereby, the aquifer. New drilling information, additional surface exposures, and new methods of seismic reflection profiling will improve the accuracy of the subsurface geologic interpretations and ground-water flow modeling.

GEOLOGIC SETTING

The Spokane Valley owes its present form and character to multiple geologic processes. The oldest postulated basin in this area is defined by pre-Tertiary granites and gneisses (Weis, 1968; Weissenborn and Weis, 1976). These rocks are unconformably overlain by Miocene Columbia River flood basalts and the Latah Formation. The Latah Formation consists of lacustrine sediments and associated prograding deltaic deposits that were laid down where basalt flows dammed streams (Pardee and Bryan, 1926).

Erosion and deposition by late Pleistocene catastrophic flooding resulted in deep anastomosing channels carved into the granites, gneisses, basalts, and lake sediments and left the numerous large-scale fluvial depositional forms visible in today's landscape. These forms include, among others, pendant bars, eddy bars, and terraces. Pendant bars form downstream of a bedrock protrusion where a decrease in flow velocity induces deposition. This results in foreset beds that generally dip downstream. Eddy bars form at the confluence of tributary valleys with the main valley; here, flow velocities decrease and often reverse direction in a circulating pattern. The varying directions of sediment transport are recorded in the various orientations of cross-bedded silts, sands, and gravels.

The first to attribute the present-day morphology of the Channeled Scablands of eastern Washington to catastrophic flooding was J Harlan Bretz in 1923. At the time, and for at least 30 years thereafter, his theories were the subject of skepticism and ridicule from his contemporaries. It was not until the 1950s and 1960s that the Bretz hypothesis was accepted. A Pleistocene glacial lake, named Lake Missoula, was identified as the source for the tremendous amounts of water necessary to create these floods. Most researchers now agree that numerous catastrophic late Pleistocene (and maybe earlier) glacial outburst floods are responsible for today's "Channeled Scabland" and associated deposits. Deep coulees, dry falls, potholes, and thick deposits of sorted sediment ranging in size from cobbles and boulders to silts and clays are evidence of the Missoula Floods and their back eddies and slack water. Waitt (1980, 1985), Atwater (1986), Kiver and others (1989), and others have concluded that the floods numbered at least 40, possibly more. Stratigraphic relations of flood sediments with St. Helens set S and Glacier Peak tephra suggest that the last great flood occurred between 11,250 and 13,000 years ago (Stradling and Kiver, 1986; Carrara and Trimble, 1992).

Loess (windblown silt) commonly covers the high plateaus (known locally as prairies), and reworked loess, volcanic ash (from the eruption that formed Crater Lake ~7000 years ago), and sands are exposed as dunes in an area just north of Spokane. There are no known deposits of till or glacial outwash in the Spokane area. The lack of these deposits and the identification of terminal moraines to the north suggest that continental ice did not extend as far south as Spokane and that any outwash deposits were either reworked by the Missoula Floods or diverted westward north of Spokane.

The deposits left by the Missoula Floods make up the Spokane Valley–Rathdrum Prairie Aquifer and are the subject of this mapping project.

PROCEDURE

The aquifer project is divided into several phases. The initial phase is to compile and update maps of surficial deposits at a scale of 1:24,000. Building on the unpublished Quaternary mapping by E. P. Kiver and D. F. Stradling, done in the 1970s and early 1980s, and on various published sources of bedrock mapping, project workers are using aerial photographs and field work to help confirm contacts, to provide new data, and to prepare detailed maps of geomorphic features of the flood deposits (Fig. 2). Recent foundation excavations, percolation test pits, quarries, and roadcuts are providing countless exposures for this purpose (Fig. 3A–D). Subsurface stratigraphic data collected from water-well logs obtained from the Department of Ecology are being used to improve the accuracy of

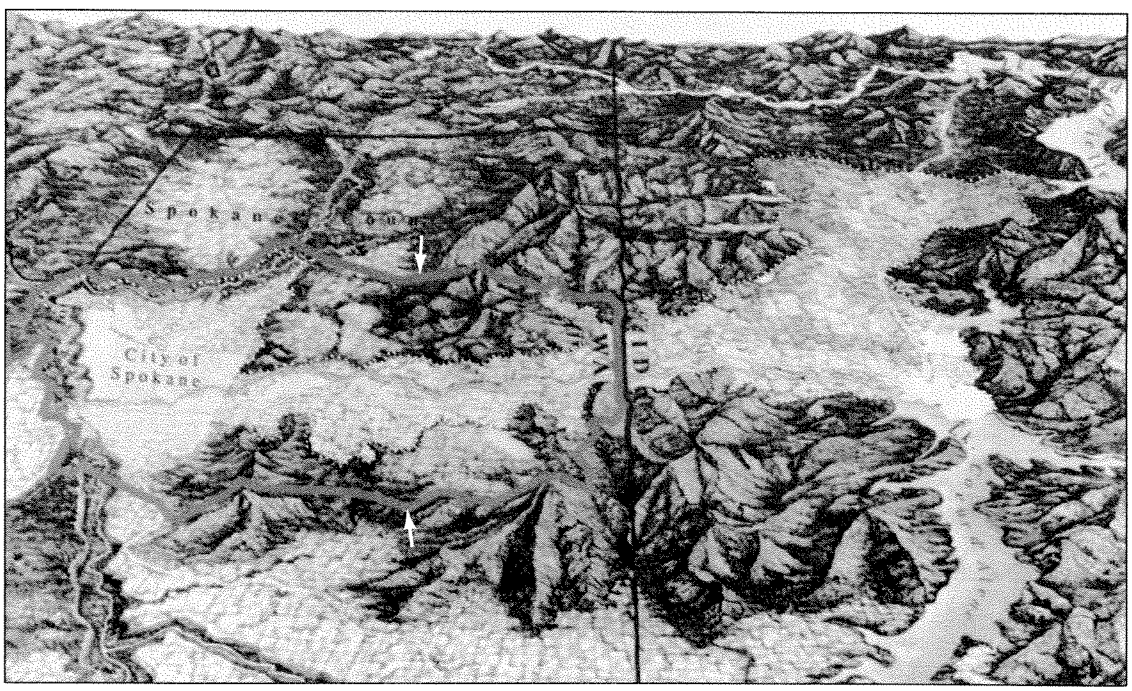

Figure 1. Oblique view of the area of the Spokane Valley–Rathdrum Prairie Aquifer. Broad gray line indicated by white arrows outlines the Spokane Valley Critical Aquifer Recharge Area. (Drawing by Emily Johnson.)

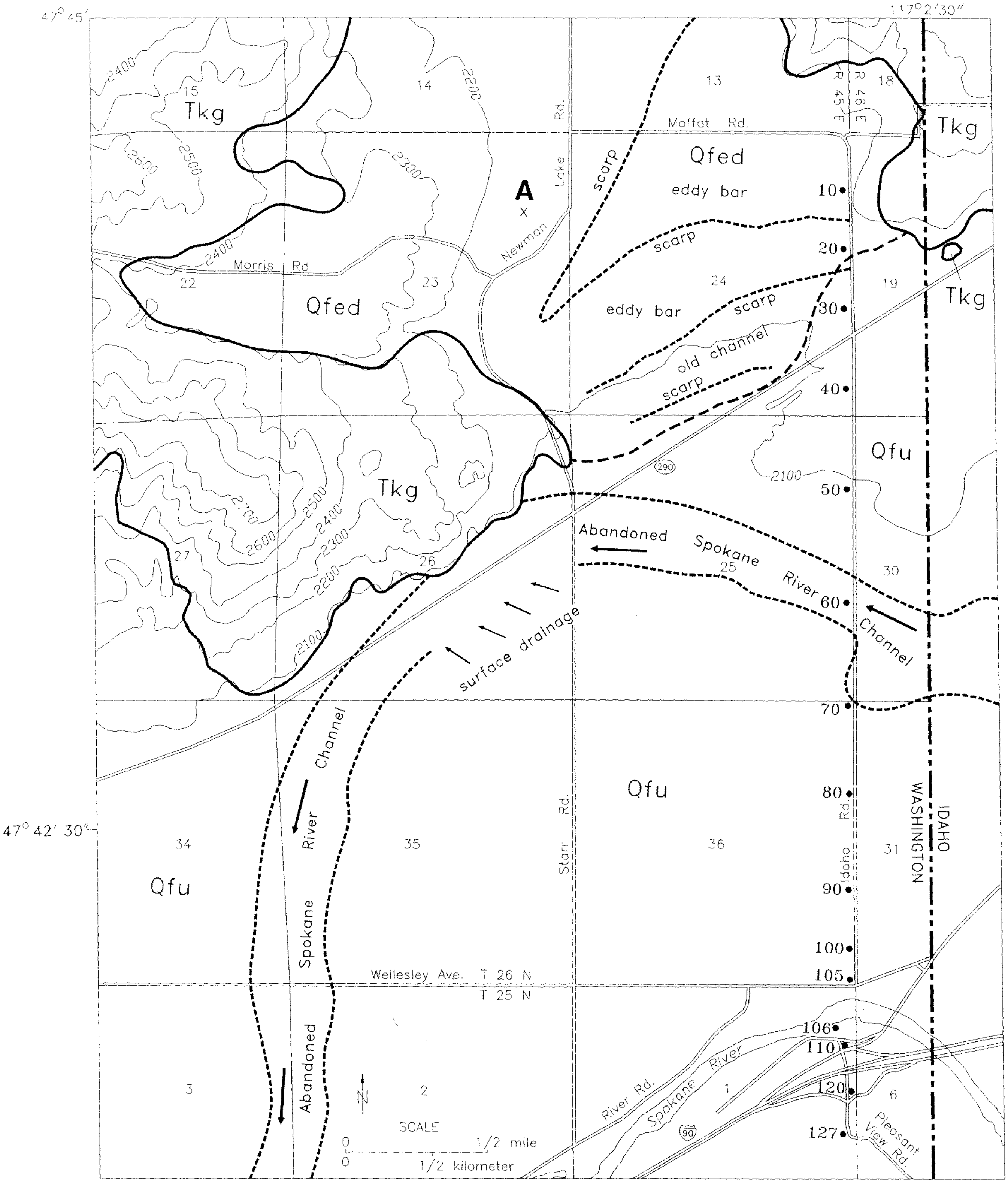

Figure 2. Geology and geomorphology near the Washington–Idaho state line, showing the location of the abandoned channel of the Spokane River and eddy bar deposits. Mapped units: Qfed, Missoula Flood eddy bar deposit; Qfu, Missoula Flood deposit undifferentiated; Tkg, Tertiary–Cretaceous granites and gneisses. Location A refers to bottom right photo of Figure 3. A preliminary interpreted geologic cross section along Idaho Road is shown in Figure 4. This figure also shows the location of the Idaho Road seismic reflection profile (Fig. 5).

the surficial mapping, as well as to construct geologic cross sections (Fig. 4).

Another phase of the project is using seismic reflection profiling to map the depth to the water table and to the bedrock surface underlying the aquifer. In a seismic reflection sounding an acoustic pulse (a shock wave) is generated by a source on the ground surface. The pulse travels downward through the surficial and underlying sediments. As the pulse reaches

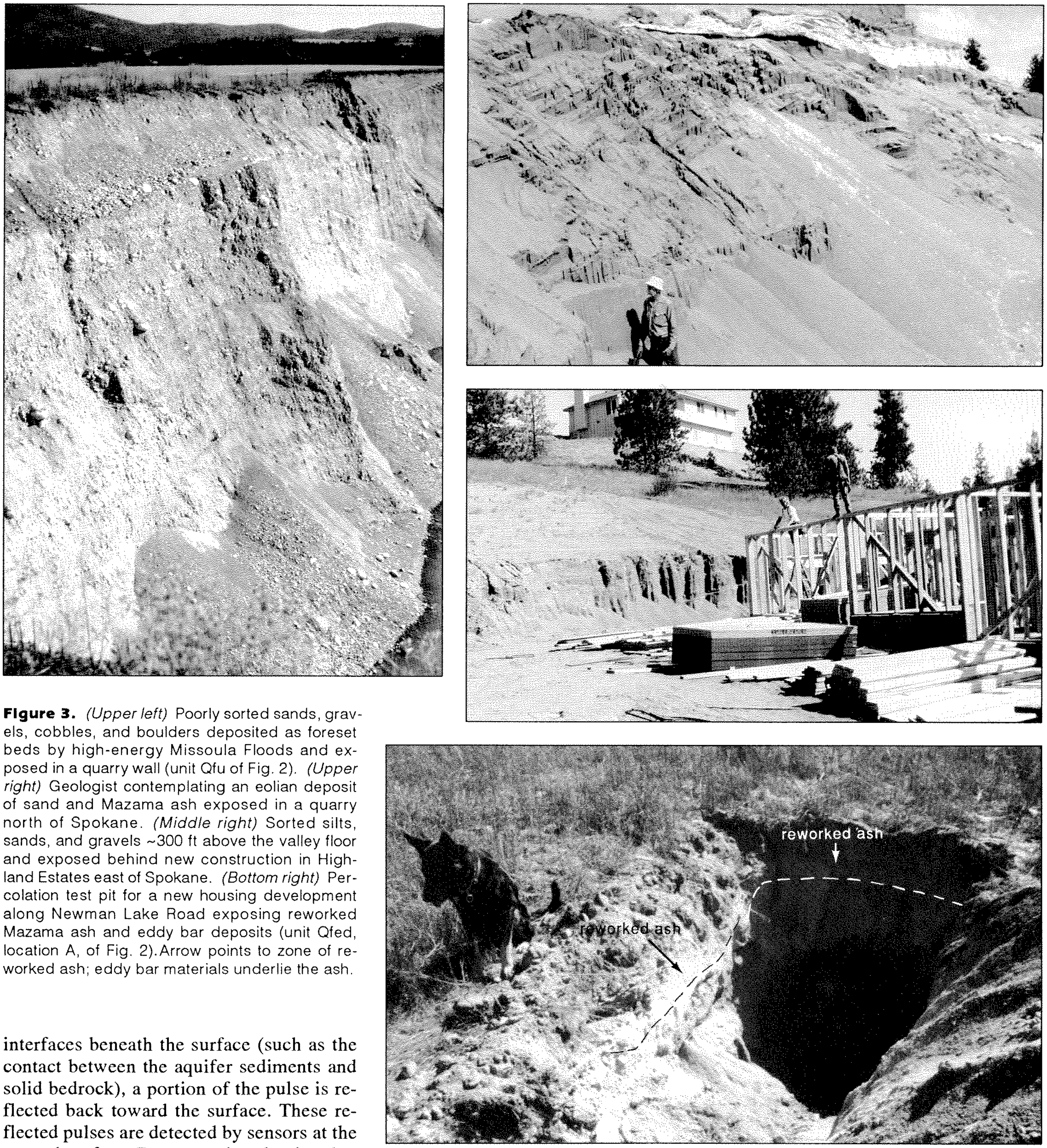

Figure 3. *(Upper left)* Poorly sorted sands, gravels, cobbles, and boulders deposited as foreset beds by high-energy Missoula Floods and exposed in a quarry wall (unit Qfu of Fig. 2). *(Upper right)* Geologist contemplating an eolian deposit of sand and Mazama ash exposed in a quarry north of Spokane. *(Middle right)* Sorted silts, sands, and gravels ~300 ft above the valley floor and exposed behind new construction in Highland Estates east of Spokane. *(Bottom right)* Percolation test pit for a new housing development along Newman Lake Road exposing reworked Mazama ash and eddy bar deposits (unit Qfed, location A, of Fig. 2). Arrow points to zone of reworked ash; eddy bar materials underlie the ash.

interfaces beneath the surface (such as the contact between the aquifer sediments and solid bedrock), a portion of the pulse is reflected back toward the surface. These reflected pulses are detected by sensors at the ground surface. By measuring the time between the initiation of the acoustic pulse and the arrival of the reflected pulses, it is possible to estimate the depth of the interfaces from which the reflections originate.

Figure 2 shows the locations of the shotpoints for the seismic reflection profile acquired along Idaho Road in the eastern part of the aquifer study area. A shotpoint is the location of an individual seismic reflection sounding, and the profile is constructed by merging information from a large number of individual soundings. Figure 5 shows the preliminary seismic reflection profile from Idaho Road. Six seismic lines are planned for this project; some of these will intersect to improve the data interpretation.

DISCUSSION

Some interesting information is 'surfacing' from the geomorphic, water-well log, and seismic data. A few miles east of Spokane, aerial-photo reconnaissance and field mapping re-

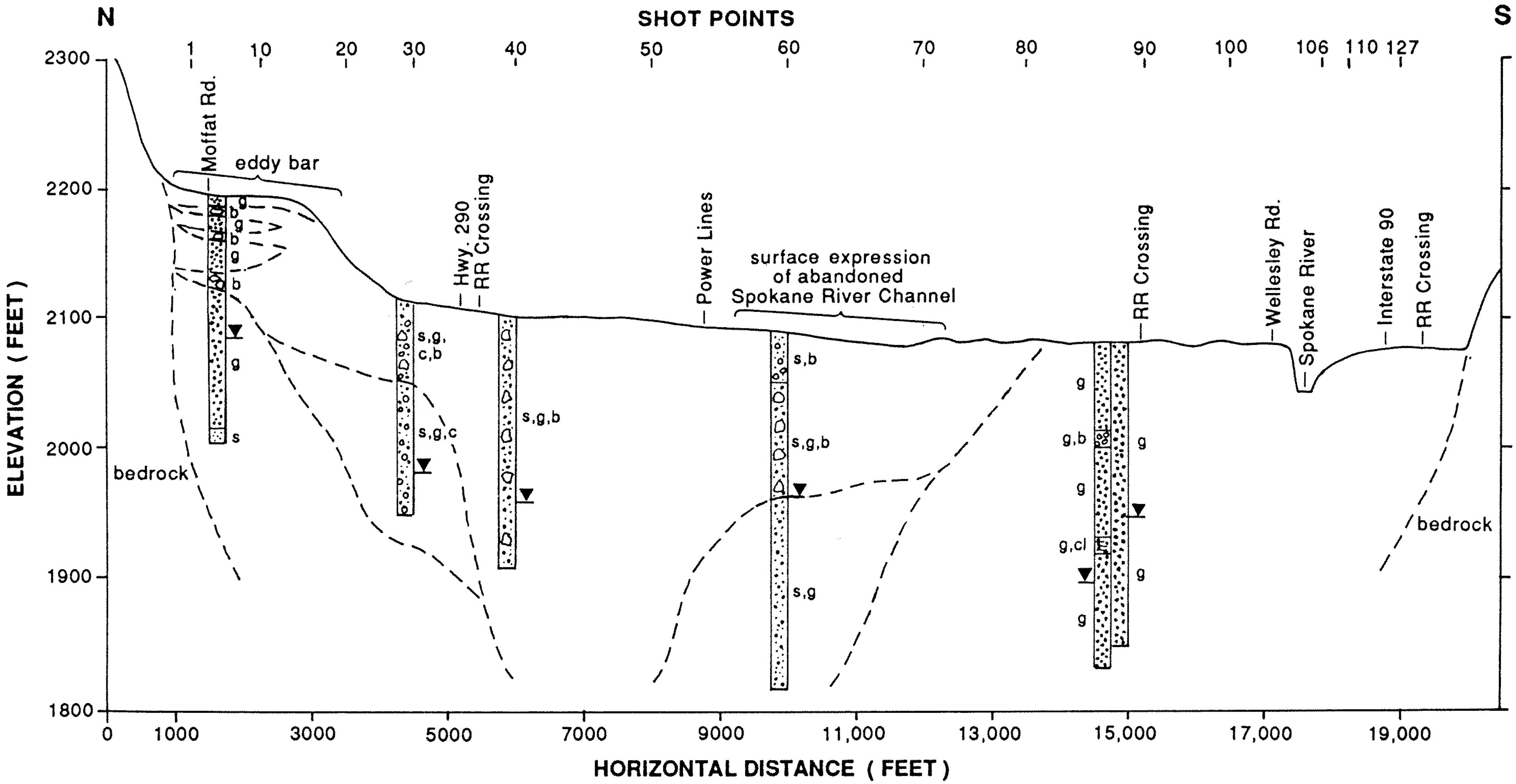

Figure 4. Preliminary interpreted geologic cross section along Idaho Road, based on mapping of surficial deposits, water-well log data, and results of seismic-reflection profiling. s, sand; g, gravel; b, boulders; c, cobbles; cl, clay. See Figure 2 for location of Idaho Road. Vertical exaggeration 20X.

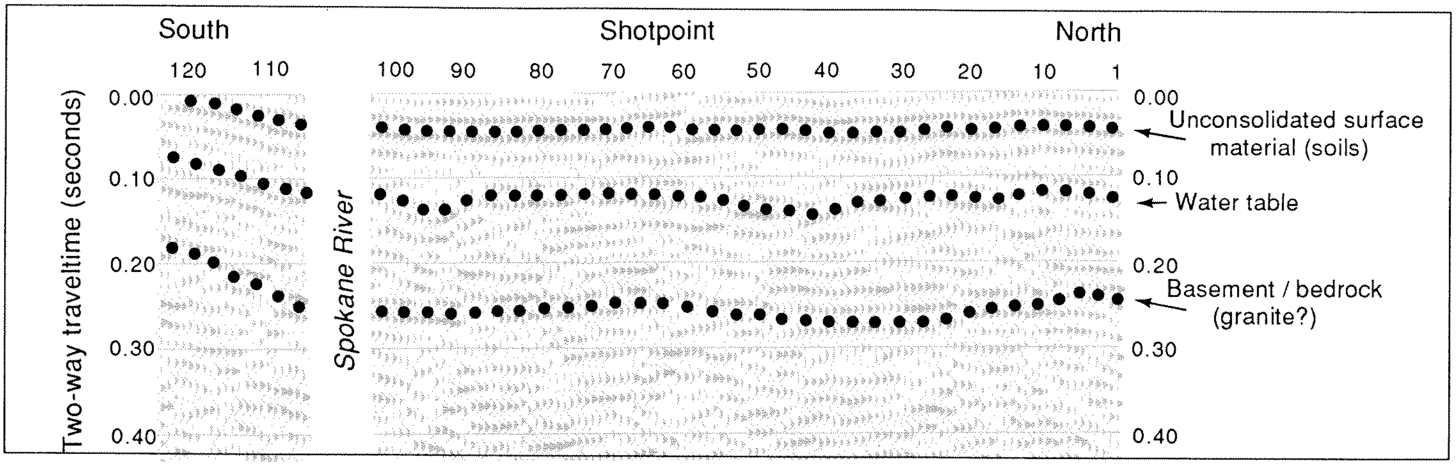

Figure 5. Example of a seismic-reflection profile along Idaho Road near Spokane.

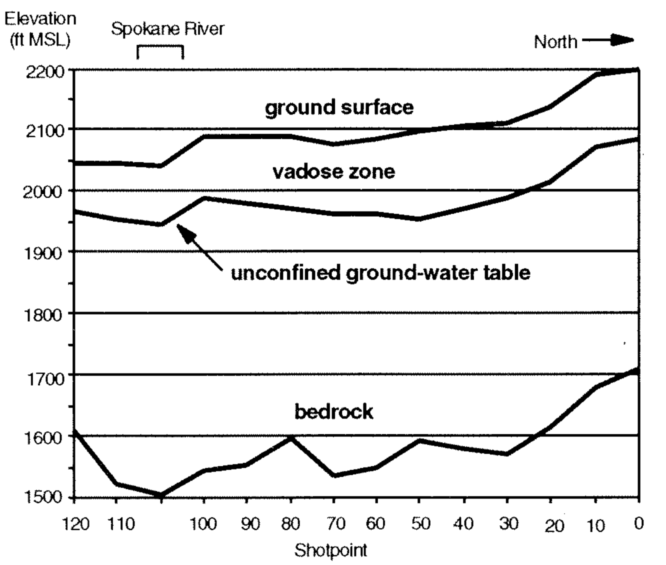

Figure 6. Seismic cross section along Idaho Road, derived from the data shown in Figure 5.

veal a broad abandoned channel of the Spokane River to the north of the present-day channel (Fig. 2). Seismic data from this location also suggest such a feature in the bedrock surface (Figs. 5 and 6). And in the same area, water-well log data suggest a zone of less consolidated and coarser material than in adjacent areas of the valley. Coarser sediments result in higher transmissivity (the rate at which water travels through a unit width of the aquifer under a unit of hydraulic gradient). A zone of high transmissivity could have either negative or positive consequences for aquifer use, depending on the geometry and lateral continuity of that zone. This introduces an important consideration in tracking pollutants and planning aquifer use.

Figure 6 is a cross section developed from the seismic data collected along Idaho Road. It shows the depth from the surface to the water table and to the bedrock underlying the Spokane Aquifer along this seismic profile. The cross section shows that the aquifer is approximately 500–550 ft thick in the central part of the profile and that the bedrock surface has subdued topography; the postulated channel morphology is located between shotpoints 35 and 70 (Figs. 5 and 6). The cross section also shows that the water table is approximately 100–150 ft below the ground surface in the center of the valley. The north end of the seismic profile shows both the bedrock surface and water table rising in the tributary valley that leads to Newman Lake (located just to the north of the area depicted in Fig. 2).

Hall's (1991) assessment of small drainage basins marginal to the Spokane Valley shows that their water quality is deteriorating because ground-water flow through the area is slow, contaminant residence times are longer here than in the main part of the valley, and dilution is not very effective. Characteristics of the bedrock morphology identified during this investigation could help explain the degradation noted by Hall. In several places, broad bedrock protrusions or shelves, not exposed at the surface, extend from the valley margins into the main valley. This configuration suggests that the aquifer depth, and possibly width, are less than present models predict in these locations. As in the case of the abandoned channel, these bedrock features would have a significant effect on the flow velocities and directions within the aquifer.

The deteriorating water quality suggests that effluent from the high density of septic systems associated with rapid hillside development exceeds the natural filtering capacity of the aquifer at its margins. Hall (1991) points out that the Water Quality Management Plan of 1978 addressed the issues of water-quality degradation by specifying low-density development in the hillside areas, but that these recommendations were abandoned when the sewer plan was expanded to serve a larger area and more homes. That plan, however, has not been implemented. Field observations show that recent and ongoing development is not only being carried out at a greater density than the recommended single residence per 2-acre tract, but also that most of the hillside homes are still being constructed with septic systems rather than being linked to a sewer system.

CONCLUSIONS

Zones of varied sediment sizes and sorting in the Spokane Valley Aquifer, as well as the configuration of bedrock beneath the aquifer, have important implications for Spokane County's aquifer management planning program. Thick deposits of poorly consolidated, coarse material can transmit larger volumes of ground water and (or) contaminants at relatively high velocities. In contrast, thin zones of finer material suggest lower rates of ground-water and contaminant flow; there is also the potential in these areas for ground-water stagnation and the associated deterioration of water quality.

Information gathered in this study is delineating the different potential flow regimes in greater detail than accomplished by earlier studies, and it therefore can be used to design new ground-water flow models. Improved models will reduce the risks of degrading the water quality or the health of water users. Residents of the Spokane Valley, or any community that relies on ground water, need to be aware that any discharge to the ground water in the form of industrial and residential pollutants is likely to be withdrawn from the aquifer in drinking water. Inputs to an aquifer system are fully integrated with outputs, and neither can be exploited indiscriminately. The information provided by a joint, interdisciplinary project such as this one is a valuable tool in managing and preserving an invaluable resource.

ACKNOWLEDGEMENTS

Seismic reflection data and collaborative geologic interpretation provided by Mike King and Scott Clark of SeisPulse Development Corp. have improved the information produced by this project and the potential for accurate three-dimensional modeling of the Spokane Aquifer. Reviews by our colleagues, especially Chuck Gulick, have improved the manuscript. Chuck's contacts and earlier work with staff of the Spokane County Water Quality Management Program provided important insight on the implications of sole source aquifer designation and management. Bob Derkey's ideas and perseverance made the project possible.

REFERENCES

Atwater, B. F., 1986, Pleistocene glacial-lake deposits of the Sanpoil River valley, northeastern Washington: U.S. Geological Survey Bulletin 1661, 39 p., 3 pl.

Bolke, E. L.; Vaccaro, J. J., 1979, Selected hydrologic data for Spokane Valley, Spokane, Washington, 1977–78: U.S. Geological Survey Open-File Report 79-333, 98 p., 1 pl.

Bolke, E. L.; Vaccaro, J. J., 1981, Digital-model simulation of the hydrologic flow system, with emphasis on ground water, in the Spokane Valley, Washington and Idaho: U.S. Geological Survey Water-Resources Investigations Open-File Report 80-1300, 43 p.

Bretz, J H., 1923, The Channeled Scablands of the Columbia Plateau: Journal of Geology, v. 31, no. 8, p. 617-649.

Carrara, P. E.; Trimble, D. A., 1992, A Glacier Peak and Mount Saint Helens J volcanic ash couplet and the timing of deglaciation in the Colville Valley area, Washington: Canadian Journal of Earth Sciences, v. 29, no. 11, p. 2397-2405.

Dion, N. P., 1987, Geohydrologic reconnaissance of a ground-water contamination problem in the Argonne Road area near Spokane, Washington: U.S. Geological Survey Water-Resources Investigations Report 86-4173, 37 p.

Drost, B. W.; Seitz, H. R., 1978, Spokane Valley–Rathdrum Prairie Aquifer, Washington and Idaho: U.S. Geological Survey Open-File Report 77-829, 79 p., 10 pl.

Hall, T. L, 1991, Effects of hillslope development on quantity and quality of recharge to the Spokane aquifer, Spokane, Washington: Eastern Washington University Master of Science thesis, 133 p.

Kiver, E. P.; Stradling, D. F.; Breckenridge, R. M.; McDonald, E. V.; Busacca, A. J., 1989, The Channeled Scabland—Lake Missoula floods and sediments and loess stratigraphy. *In* Joseph, N. L., and others, editors, Geologic guidebook for Washington and adjacent areas: Washington Division of Geology and Earth Resources Information Circular 86, p. 305-346.

Lackaff, B. B.; Hunt, B. J.; Von Essen, I. E., 1993, The development and implementation of a GIS-based contaminant source inventory over the Spokane aquifer, Spokane County, Washington: Water Resources Bulletin, v. 29, no. 6, p. 949-955.

Newcomb, R. C.; and others, 1953, Seismic cross sections across the Spokane River Valley and the Hillyard Trough, Idaho and Washington: U.S. Geological Survey Open-File Report 53-199, 16 p.

Pardee, J. T.; Bryan, Kirk, 1925, Geology of the Latah formation in relation to the lavas of Columbia Plateau near Spokane, Washington: U.S. Geological Survey Professional Paper 140-A, p. 1-16.

Purves, W. J., 1969, The stratigraphic control of groundwater through the Spokane Valley: Washington State University Master of Science thesis, 213 p.

Stradling, D. F.; Kiver, E. P., 1986, The significance of volcanic ash as a stratigraphic marker for the late Pleistocene in northeastern Washington. *In* Keller, S. A. C., editor, Mount St. Helens—Five years later: Eastern Washington University Press, p. 120-126.

Waitt, R. B., 1980, About forty last-glacial Lake Missoula jökulhlaups through southern Washington: Journal of Geology, v. 88, no. 6, p. 653-679.

Waitt, R. B., 1985, Case for periodic, colossal jökulhlaups from Pleistocene glacial Lake Missoula: Geological Society of America Bulletin, v. 96, no. 10, p. 1271-1286.

Weis, P. L., 1968, Geologic map of the Greenacres quadrangle, Washington and Idaho: U.S. Geological Survey Geologic Quadrangle Map GQ-734, 4 p., 1 sheet, scale 1:62,500.

Weissenborn, A. E.; Weis, P. L., 1976, Geologic map of the Mount Spokane quadrangle, Spokane County, Washington, and Kootenai and Bonner Counties, Idaho: U.S. Geological Survey Geologic Quadrangle Map GQ-1336, 1 sheet, scale 1:62,500. ■

Earthquake Map Available

The full-color map "Earthquakes of Washington and Oregon, 1872–1993" is now available as USGS Open-File Report 94-226A. It sells for $12 for a plain copy; $22 for a laminated copy. Order from: U.S. Geological Survey, National Earthquake Information Center, Box 25046, Mail Stop 967, Denver Federal Center, Denver, CO 80225. Price includes shipping and handling; add $6 for shipping outside the U.S.

Volcanic Hazards in Washington—A Growth Management Perspective

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Washington is home to five major composite volcanoes or stratovolcanoes: Mount Baker, Glacier Peak, Mount Rainier, Mount St. Helens, and Mount Adams. These volcanoes and Mount Hood to the south in Oregon are part of the Cascade Range, a volcanic arc that stretches from southwestern British Columbia to northern California.

Although there are thousands of small basaltic or basaltic-andesitic volcanoes in the Cascade Range, the 13 major composite volcanic centers in the U.S., all part of the range, have been the focus of most hazards concerns. During the past 12,000 years, these volcanoes have produced more than 200 eruptions that have generated tephra (ejected material), lava flows, and lahars (volcanic debris flows) and debris avalanches (Miller, 1990). It is important to note that other enormous debris avalanches and lahars may have been caused by intrusions of magma (not eruptions) or steam explosions at the volcanoes or by local or regional earthquakes because these flowage events do not correlate with known tephra layers.

All Washington volcanoes except Mount Adams have erupted within the last 250 years (Table 1). Mount Hood erupted in the late 1700s and into the mid-1800s (Crandell, 1980; Cameron and Pringle, 1987). However, the volcanoes do not erupt at regular intervals, thus making it difficult to forecast when a given volcano might come to life again. Although worldwide the risks from volcanoes are significantly lower than risks from earthquakes and landslides, the relatively long recurrence interval for volcanic hazards (decades to several centuries) combined with their great potential for destruction make them particularly insidious.

This article will focus mainly on the volcanic hazards associated with the five Washington volcanoes and Mount Hood, although other volcanic areas, such as the Indian Heaven volcanic field southwest of Mount Adams, have erupted during the Holocene (10,000 years ago to present). Also, this article briefly reviews the terminology used to communicate volcanic hazards information and provides an overview of volcanic processes and hazards in Washington State with particular emphasis on how they relate to the Washington Growth Management Act (GMA). Additional information resources are listed at the end of the article.

VOLCANIC HAZARDS AND THE PLANNING PROCESS

The GMA mandates comprehensive planning in some jurisdictions. This mandated planning effort includes delineation of geologically hazardous areas (including volcanic hazard areas) as the initial planning step and subsequent formulation of regulations governing development in hazardous areas. To this end, in December of 1990, the Department of Community Development (now the Department of Community, Trade and Economic Development) issued minimum guidelines for classifying volcanic hazards with respect to the GMA:

> *Volcanic hazard areas shall include areas subject to pyroclastic flows, lava flows, debris avalanche, inundation by debris flows, mudflows or related flooding resulting from volcanic activity.*

Certain volcanic hazards, such as fallout of tephra and tsunamis, although important, were not included in the guidelines. Tephra fallout hazards, for example, are extremely widespread in volcanic terrains, and the proximal hazard zones shown in Figure 1 already include the areas that have the highest probability of destructive tephra fallout. Hoblitt and others (1987) discuss tephra hazards with respect to the siting of nuclear power plants, and Casadevall (1992, 1993) addresses the problem of volcanic ash and aviation safety.

As will be noted below, evidence for the hazardous volcanic processes mentioned in the GMA guidelines has been observed in the geologic records of various Cascade volcanoes (Crandell and Waldron, 1973; Miller, 1990). Before the cataclysmic eruption of Mount St. Helens in 1980, roughly 30 person-years had been devoted to analysis of volcanic hazards in

Table 1. Major volcanoes and volcanic fields in Washington and northernmost Oregon

Volcano	Eruption type(s)	No. of eruptions in past 200 yrs	Latest activity (yr A.D.)	Remarks about activity of the last 10,000 years
Mount Baker	ash, lava	1?	mid-1800s; 1870?; 1975 steam emission	debris avalanches and lahars have flowed down the Nooksack, Baker, and Skagit Rivers
Glacier Peak	ash	1+?	before 1800	lahars have extended more than 60 mi (100 km) down the Skagit River; pyroclastic flows produced several times
Mount Rainier	ash, lava	1?	X tephra between 1820–1854	enormous debris avalanches and lahars flowed down the White, Puyallup, and Nisqually Rivers; smaller lahars in the Cowlitz basin; continued seismic activity
Mount St. Helens	ash, lava, dome	2 major eruptive periods	1980–present	history of explosive eruptions and lahars
Indian Heaven volcanic field	lava, scoria	none	8,000 yr ago?	consists of seven minor shield volcanoes that have each erupted only once (?)
Mount Adams	lava, ash	none	3,500 yr ago	lahars
Mount Hood, Oregon	ash, dome	2+?	1865; major eruption in the late 1700s	lahars down the Sandy and Hood Rivers; modern glacial outburst floods; seismic swarms continue

the Cascade Range. While much has been learned about the history of the Cascade volcanoes because of these early studies, more geologic investigations are necessary in order to bring some of the older hazards assessments up to date with our current understanding of volcanic processes. Furthermore, some inconsistencies exist in the understanding of hazards from individual volcanoes because some (such as Mount St. Helens) have been studied in considerably greater detail than others (for example, Glacier Peak and Mount Baker).

Volcanic hazards are destructive volcanic processes that have a definite probability of occurring. In order to best understand the importance of considering volcanic processes and hazards in the planning process, it is helpful briefly to review the concept of risk, the magnitude of the loss. Risk can be expressed as a function of the hazard, value that could be lost (lives, property, stock, etc.), and vulnerability (generally speaking, preparedness). Using this definition, it is all too clear that the number of lives and amount of property at risk to volcanic hazards in Washington is rapidly growing as development spreads into hazardous areas, such as valleys that drain active volcanoes. While most of these communities had at least twice the population in 1990 that they had in 1950, at least one, Kent, has had a ten-fold increase!

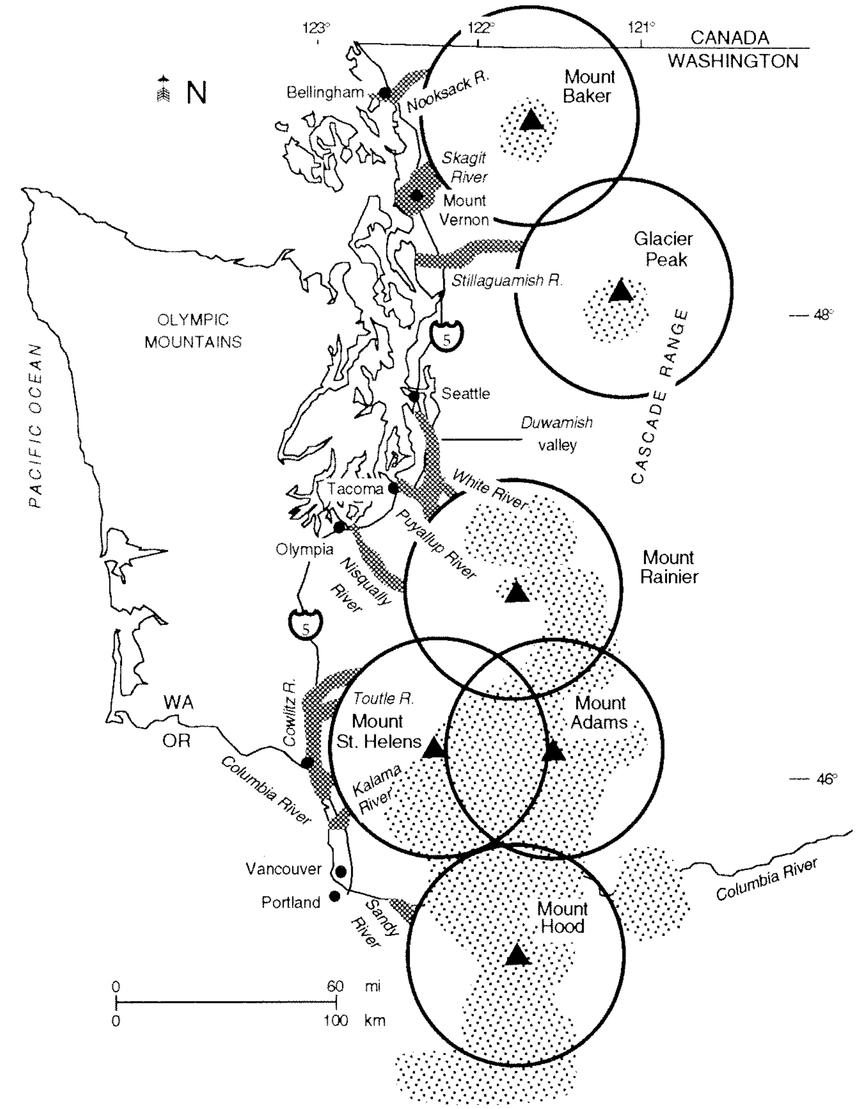

Figure 1. Diagrammatic representation of volcanic hazard zones in the Cascade Range in Washington and northern Oregon, modified from Hoblitt and others (1987). Circles show proximal hazard zones with a radius of 50 km; stippled pattern shows hazards from eruptions of basaltic volcanoes and volcanic fields; crosshatched pattern shows distal lahar and laharic-flood hazard zones. Some valleys, such as the Skagit or Puyallup, face a higher hazard of lahars than other valleys, such as the Stillaguamish.

VOLCANIC PROCESSES AND HAZARDOUS VOLCANIC EVENTS

The following discussion focuses on volcanic processes and hazards, particularly those mentioned in the GMA guidelines. For a more complete discussion of this topic, chapter 2 in Tilling (1989) is an excellent reference.

Generally, composite volcanoes are associated with subduction zones. Consequently, they are found around the Pacific Rim ("Ring of Fire") and in the Mediterranean–Himalayan Belt. They are mainly characterized by the following processes, features, or aspects.

Lava Domes and Flows

Lavas of higher viscosity tend to pile up and form domes because they cannot flow as readily as those having lower viscosity (such as Hawaiian basaltic lavas). The new Lava Dome at Mount St. Helens was constructed during 17 episodes of activity from 1980 to 1986 that included both intrusion of new magma into the dome and extrusion of lobes of lava onto the dome's surface and flanks. Crater Rock at Mount Hood is a remnant of a dome that was constructed by eruptions during the last 1,800 years. Hazards from lava domes include explosions and collapses. Dome collapse can produce pyroclastic flows and surges, lahars, and floods.

The main hazard from lava flows is damage or total destruction by burying, crushing, or burning everything in their paths. (However, more viscous lava flows do not typically flow far from the volcano.) Lava flows can melt snow and ice, but they generally do not produce major floods and lahars because they do not mix turbulently with snow and ice. They can, however, melt large quantities of ice, which can be released as "jökulhlaups" or glacial outburst floods.

Pyroclastic Density Currents

Pyroclastic density current is a general name for various types of flows of hot gas and rock down the slopes of a volcano. These geologic processes, which include pyroclastic flows, pyroclastic surges, and lateral blasts, generally only affect areas relatively close to the volcano.

Pyroclastic flows are masses of hot (300°–800+°C), dry pyroclastic debris and gases that move rapidly along the ground surface at velocities ranging from ten to several hundred meters per second. Typical pyroclastic flows have two components: (1) a ground-hugging, dense, basal portion (the flow), and (2) a preceding or overriding turbulent ash-cloud surge that has separated from the flow.

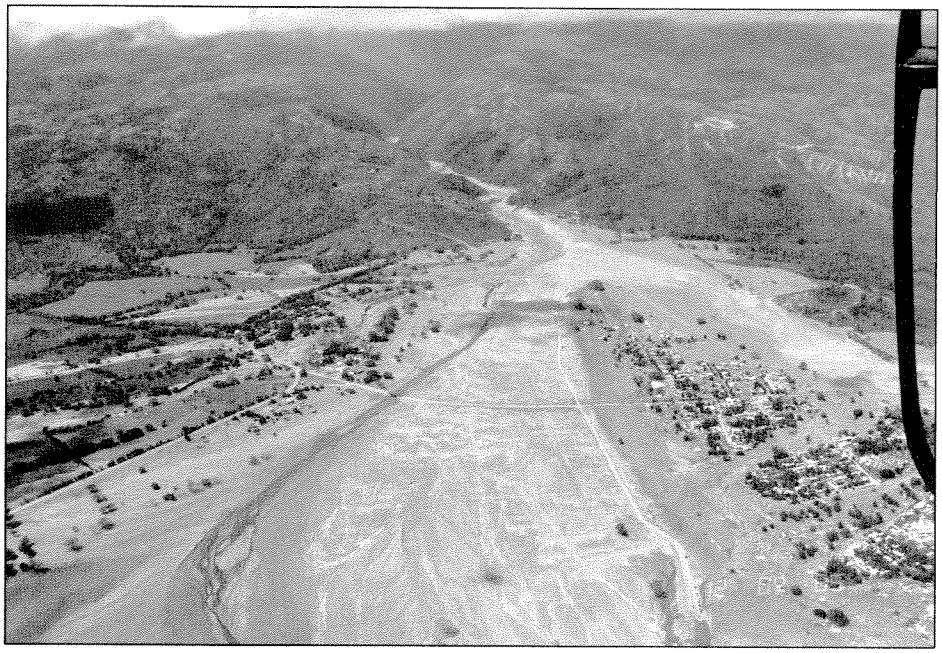

Figure 2. Upstream view of the village of Armero, Colombia, about 50 km downstream of Nevado del Ruiz. On November 13, 1985, during a fairly small eruption, the volcano generated a lahar that killed more than 20,000 people and produced this devastation. Photo by Dick

Figure 3. Upstream (southeast) view of the Puyallup River valley about 50 km downstream of Mount Rainier. The town of Orting is visible on the left edge of the photo. The valley bottom is underlain by a stack of lahars and alluvial deposits from Mount Rainier.

Direct hazards of pyroclastic flows are asphyxiation, burial, incineration, and impact. Pyroclastic flows also can generate lahars and floods by quickly melting snow and ice, can dam tributary valleys, and can start fires. Pyroclastic flows are strongly controlled by topography and are likely to be restricted to valley floors. Although most pyroclastic flows would be limited to within about 15 mi (25 km) of a volcano, Heller and Dethier (1981) noted Holocene pyroclastic flow deposits about 18 mi (30 km) from Mount Baker in the Baker valley.

Unlike pyroclastic flows, hot pyroclastic surges, because they are less concentrated and less dense than pyroclastic flows, are not necessarily confined to valleys and can affect more extensive areas many tens of kilometers from the volcano. Hot pyroclastic surges can generate secondary pyroclastic flows. Surges are responsible for many catastrophes, including 30,000 deaths at Mount Peleé (1902) and 2,000 at El Chichón (1982). Cold, or base, surges typically result from explosive interactions of magma with water, such as that at Kilauea, Hawaii, in May of 1924 and, on a smaller scale, the post-1980 phreatic (steam) explosions on the Pumice Plain and in the crater at Mount St. Helens.

Another possible hazard from Cascade volcanoes is the directed blast. Directed blasts are very powerful, laterally directed explosions such as that at Mount St. Helens in 1980 and at Bezymianny, Kamchatka, in 1956. Blasts can affect large areas (230 mi^2 or 600 km^2 at Mount St. Helens).

Lahars, Lahar-Runout Flows, and Floods

Lahars are volcanic debris flows ("mudflows") or rapidly flowing mixtures of rock debris mobilized by water that originate on the slopes of a volcano (Figs. 2 and 3). Most are restricted to stream valleys. Although there are many causes of lahars, two major flow types have been noted, granular and muddy[1].

Granular lahars

Granular lahars have a relatively low clay content (<4%). These flows typically begin as a flood surge that incorporates sediment and becomes a debris flow as it travels. The debris flow then rapidly transforms downstream to more diluted flow types (lahar-runout flows, floods). The many causes of these clay-poor lahars include:

- Interaction of a pyroclastic density current with snow and ice
- Meteorologically (rainstorm or rain-on-snow events) induced erosion of tephra (or other fragmental debris) from the slopes of a volcano
- Failure of a landslide-dammed lake
- Glacial outburst flood (jökulhlaup)

[1] Granular lahars are sometimes called "noncohesive lahars", and muddy lahars are termed "cohesive lahars" by some researchers. The terms cohesive and noncohesive are not used in the rigorous manner of engineering soil scientists.

Muddy lahars

Muddy lahars are relatively clay-rich (>4%) and typically originate as "sector collapses" of a significant portion of a volcano. They can be triggered by earthquakes, steam explosions, intrusions, or by other destabilization (not necessarily by eruptions). Muddy lahars can have enormous volumes and flow great distances. The Electron and Osceola Mudflows at Mount Rainier and the Middle Fork Nooksack flow at Mount Baker are local examples. The volume of the Electron Mudflow has been estimated at more than 300 million yd^3 (0.25 km^3) and the volume of the Osceola Mudflow at more than 0.7 mi^3 (3 km^3)(Scott and others, 1992).

Inundation height, runout length, velocity, and duration of flood wave for lahars can vary widely. The elapsed time between events, amount of available sediment for bulking, and other factors can change the scale of the hazard from lahars. In general, relative risk decreases with distance downvalley and with height above the valley floor.

Table 2. Design or planning examples of lahars at Mount Rainier, an example of a probabilistic hazard assessment. NA, not applicable (Modified from Scott and others, 1992, p. 79)

	Maximum lahar	Case I	Case II	Case III
Debris flow type	Muddy (cohesive	Muddy (cohesive	Granular (noncohesive)	Probably muddy but may be partly or entirely granular, depending on source area
Recurrence interval	~10,000 yr	500–1,000 yr	100–500 yr	<100 yr
Volume at lowland boundary	>3 km^3	230x10^6 m^3	60x10^6 m^3 (Puyallup River) 65x10^6 m^3 (Carbon River)	NA
Mean flow velocity				
Base of volcano	>40† m/s	>30† m/s	10 m/s	>30† m/s
Lowland boundary	>20 m/s	~20 m/s	~7 m/s	NA
1 km on lowland	~10 m/s	~8 m/s	~3–4 m/s	NA
Cross-sectional area of flow at lowland boundary	~90,000 m^2	~16,000 m^2	1,000 m^2 (Puyallup River) 1,200 m^2 (Carbon River)	NA
Peak discharge at lowland boundary	>1,800,000 m^3/s	~320,000 m^3/s	7,700 m^3/s (Puyallup River) 8,400 m^3/s (Carbon River)	NA
Depth of moving flow				
Base of volcano	~200 m	~50 m	15 m	55 m
Lowland boundary	~100 m	22 m	8 m	NA
1 km on lowland	up to 30 m	~10 m	1-3 m	NA
Sediment concentration at lowland boundary‡ (percent by volume)	>60%	>60%	~40% (Puyallup River) ~45% (Carbon River)	NA
Extent (or inundation area)	To Puget Sound or Columbia River (in Cowlitz River drainage)	Inundation of 36 km^2 (Electron) to ~50 km^2 (modern recurrence of same flow)	All active flood plains (except Cowlitz River) above reservoirs, if present; otherwise upstream of Puyallup	Runout phases of noncohesive lahar could extend an additional 10 km

† Estimated by comparison with similar flows at other volcanoes.
‡ Estimated on assumption of linear relation of sorting and concentration observed at Mount St. Helens.

Debris Avalanches

Debris avalanches are flowing mixtures of rock and soil, with or without water, that move away from a volcano at high speed. Some of these events are gigantic (>10^{18} m^3). Since the 1980 eruption of Mount St. Helens, hummocky debris avalanche deposits have been recognized at several hundred volcanoes around the world. Some debris avalanches at volcanoes have been caused by earthquakes (Ontake Volcano, Japan, 1984). Debris avalanches are an end member of a continuum of mass-wasting processes at composite volcanoes—large lahars at some highly hydrothermally altered volcanoes, such as Mount Rainier, have undoubtedly transformed directly from debris avalanches.

Geologists now realize that this type of gigantic avalanche and those that transform into lahars occur far more frequently than previously recognized. The nature of this hazard and its relation to hydrothermal alteration and destabilization of a volcanic cone also indicate that sector collapse events (very large debris avalanches) can affect any drainage that heads on a volcano. The frequency of enormous megathrust earthquakes in the Cascadia subduction zone (13 in the past 7,600 yr), as well as our increasing recognition of shallow-crustal fault zones in the Puget–Willamette Lowland and along the Cascades, amplify the need to consider this major slope-stability hazard at composite volcanoes.

The debris avalanche from Ontake Volcano (mentioned above) exemplifies this type of hazard. On September 14, 1984, a magnitude 6.8 earthquake triggered a debris avalanche that traveled about 13 km downvalley, killing 29 people. Numerous larger slope failures in the geologic record could be attributed to tectonic sesmicity. These and other uncommon events, such as the 1980 blast at Mount St. Helens, are now included in hazard assessments at composite volcanoes.

SECONDARY EFFECTS OF ERUPTIONS

The secondary effects of the 1980 Mount St. Helens eruption serve as a reminder that hazards are present long after the initial eruptive activity has ceased. At Mount St. Helens, dramatic post-eruption erosion and sedimentation and the ongoing potential of floods from lakes impounded by the 1980 debris avalanche have presented costly problems. Nearly $1 billion was spent during the first 10 years after the eruption to mitigate the downstream flood hazards.

During the first 3 years after 1980, an estimated 8 million tons of tephra were washed off hillslopes into the Toutle River system. While hillslope erosion eased somewhat after 1983, erosion of the debris avalanche and the subsequent widening and incision of this drainage system by the development of a stream network resulted in a huge sediment discharge to downstream areas. The post-eruption Toutle River became one of the most sediment-laden rivers in the world. Downstream water quality and aquatic habitat severely deteriorated, and increased downstream flooding due to sediment-filled river channels jeopardized homes and roads built near the river.

Numerous natural dams were created by the debris avalanche in the North Fork Toutle River drainage. On at least five occasions from 1980 to 1982, the collapse of a dam released a small lake or pond and caused minor floods. However, public concern focused on Spirit, Coldwater, and Castle Lakes, the three largest lakes impounded by the debris avalanche. Studies by geologists in the 1980s indicated that enormous floods had resulted from the breakouts of lakes in similar settings at the volcano in pre-historic times. These types of secondary hazards could affect any volcano after an eruption or sector collapse.

VOLCANIC-HAZARD ASSESSMENTS AND HAZARD-ZONATION MAPS

Volcanic-hazard assessments for Cascade Range volcanoes provide forecasts of the type and nature of eruptions and volcanic hazards that we can expect in the future and the areas that would be affected (Crandell and others, 1975; Hoblitt and others, 1987). Some of these assessments apply to a wide variety of hazards at an individual volcano (Crandell and Mullineaux, 1978), while others apply to a more specific type of hazard, such as debris flows, and may provide detailed information about their flow processes, including travel times and volumes (Scott and others, 1992). Volcanic hazards assessments are possible because geologists have reconstructed the nature of eruptive activity or hazard by using historical records and the stratigraphic history of each of these Cascade volcanoes over the past 10,000 years. These hazards studies make the assumption that future volcanic activity at each volcano will be similar in style, scale, and frequency to its past activity.

Volcanic-hazard zonation maps (Fig. 4) designate hazardous areas around a volcano. In the past, these maps have shown relative hazard (for example, low, medium, and high), although some recent reports and maps have expressed hazards in probabilistic terms (Hoblitt and others, 1987; Scott and others, 1992). Table 2 shows an example of probabilistic hazards for lahars at Mount Rainier. A series of inundation maps based on this investigation should be available soon (Scott and others, in press).

Hoblitt and others (1987) found that the most damaging volcanic events occur within 30 mi (50 km) of a volcano. Therefore, their hazard zonation map shows a *proximal-hazard zone* within this 50-km radius of a given volcano (Fig. 4). Because significant lahars have inundated valley bottoms at distances exceeding 50 mi (80 km) from Cascade Range volcanoes, Hoblitt and others (1987) also established *distal-lahar and flood-hazard zones* for the valley bottoms that extend along major drainages beyond the 50-km radius of a volcano. These zones include modern river channels, flood plains, and low terraces.

Drainages that head on a volcano are most vulnerable to proximal hazards. Other areas are less likely to be affected by all but low-probability, high-magnitude events.

PREPAREDNESS AND MITIGATION: PUBLIC AWARENESS OF VOLCANIC HAZARDS

The 1980 events at Mount St. Helens have changed not only the way volcanic hazards are studied, but also public awareness of those hazards. The three most important aspects of volcanic hazards mitigation are: (1) communication of volcano-monitoring and volcanic-hazards information by geoscientists to the public, the media, and responsible agencies;

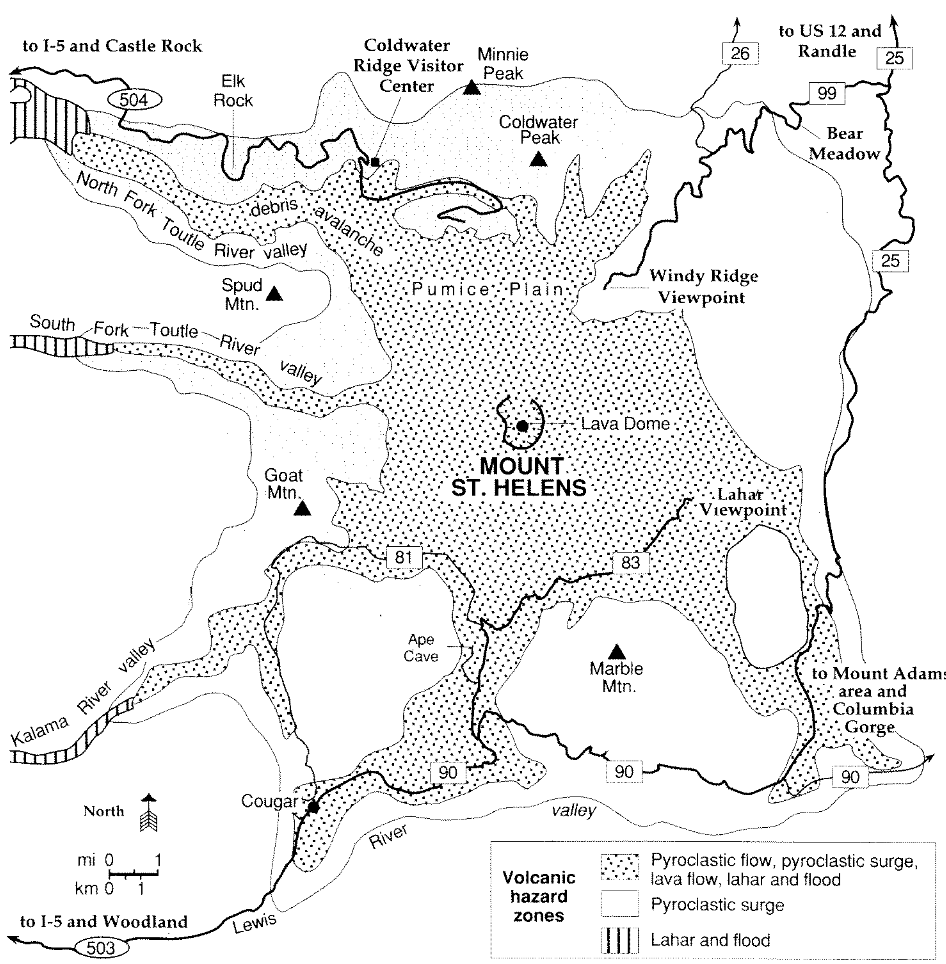

Figure 4. This preliminary volcanic hazards map, redrawn from one prepared by the U.S. Geological Survey (U.S. Forest Service, 1992), shows hazard zones close to Mount St. Helens volcano that could be at great risk in the event of a major eruption. The patterned areas would be evacuated and closed to the public. Such eruptive activity is typically preceded by a systematic increase in seismic activity that would give adequate warning. The hazard zone for lateral blasts and heavy tephra fallout would encompass the area within a 50-km radius of the volcano (beyond that shown). (Compare with Fig. 1.)

(2) emergency preparedness by responsible agencies and officials; and (3) community and regional planning and land-use designations that minimize the amount of risk. These three aspects are interrelated. Successful mitigation depends on the timely communication of understandable scientific information about the current state of the volcano, as well as the nature, extent, implications, and likelihood of the variety of volcanic processes possible at that volcano.

Communication of scientific information about the status of a volcano has improved mainly because geologists have observed Mount St. Helens so closely. Public demand for prompt and comprehensible technical information and the experience of working with an accessible volcano, such as Mount St. Helens, have helped scientists refine the communication process. As a result, geologists now use three types of public statements when describing volcanic activity:

- *Factual statements* provide information but do not anticipate future events.
- *Forecasts* are comparatively imprecise statements about the nature of expected activity (typically based on the past history and potential of a volcano and on geologic mapping).
- *Predictions* are relatively precise statements about the time, place, nature, and size of impending activity (usually based on measurements at the volcano).

These types of public statements about Mount St. Helens and other volcanoes from Alaska to the Philippines have been accepted by the media and the public because they clarify public expectations and understanding of volcanic events and hazards.

DISCUSSION

Hoblitt and others (1987) present an excellent compilation and analysis of volcanic hazards in Washington. They established proximal- and distal-hazards zones and summarized the existing literature on Cascade Range volcanoes. Their map (about 1:2,000,000 scale) is a general guide to areas that could be affected by hazardous volcanic processes. Other larger scale maps have been, and continue to be published (Scott and others, in press) and are essential for hazard zonation by planning agencies.

Although not a direct volcanic hazard, increased liquefaction susceptibility due to earthquakes is enhanced by the presence of thick deposits of volcanic sand and gravel and generally saturated conditions in lowland areas downstream of volcanoes (Palmer and others, 1991; Pringle and Palmer, 1992). Some valley-bottom areas are susceptible to multiple hazards. Liquefaction and related ground failure during strong seismic shaking could disrupt evacuation routes. Thus, if a large debris avalanche and (or) lahar were to be triggered by a regional earthquake with attendant liquefaction and ground failures on the valley bottom and valley walls, the combined results could be disastrous.

SUMMARY

The Washington State Growth Management Act mandates that jurisdictions designate volcanic hazard areas in their comprehensive plans. Volcanic hazards occur with a frequency and on a scale that require that they be considered in comprehensive land-use plans where relevant.

Abundant scientific literature is available on the subject of volcanic processes and hazards. Some Washington volcanoes, such as Mount St. Helens, have been studied in great detail, while others, such as Mount Baker and Glacier Peak, have only had reconnaissance studies. As a result, volcanic-hazards investigations and hazard-zonation maps for individual volcanoes may be out of date or at scales that are too small to be useful to local planning agencies. Revised volcanic-hazards assessments and improved hazard-zonation maps are necessary for future planning and preparedness efforts.

RESOURCES FOR VOLCANIC HAZARDS INFORMATION

U.S. Geological Survey
Cascades Volcano Observatory
5400 MacArthur Blvd.
Vancouver, WA 98661
Phone: (206) 696-7693
Fax: 206-696-7866

U.S. Geological Survey
Earth Science Information Center (ESIC)
678 U.S. Courthouse
W. 920 Riverside Ave., Spokane, WA 99201
Phone: (509) 353-2524
Fax: (509) 456-6115

Washington State Department of Natural Resources
Division of Geology and Earth Resources Library
1111 Washington St. SE, Room 173,
PO Box 47007, Olympia, WA 98504-7007
Phone: (206) 902-1450
Fax: (206) 902-1785
Bitnet: cjmanson@carson
Internet: cjmanson@u.washington.edu

SELECTED REFERENCES—VOLCANIC HAZARDS

* Particularly informative or the latest resource for this topic or volcano

General Volcanic Hazards

Blong, R. J., 1984, Volcanic hazards—A sourcebook on the effects of eruptions: Academic Press, 424 p.

Crandell, D. R.; Booth, B.; Kusumadinata, K.; Shimozuru, D.; Walker, G. P. L.; Westercamp, D., 1984, Source-book for volcanic-hazards zonation: UNESCO Natural Hazards 4, 97 p.

Crandell, D. R.; Mullineaux, D. R., 1975, Technique and rationale of volcanic-hazards appraisals in the Cascade Range, northwestern United States: Environmental Geology, v. 1, no. 1, p. 23-32.

Hickson, C. J., 1992, Volcanic hazards and volcanism in the Canadian Cordillera. *In* Bobrowsky, Peter, editor, Geologic hazards in British Columbia—Proceedings of the Geologic Hazards '91 Workshop: British Columbia Geological Survey Branch Open File Report 1992-15, p. 35-56.

Swanson, D. A.; Casadevall, T. J.; Dzurisin, Daniel; Holcomb, R. T.; Newhall, C. G.; Malone, S. D.; Weaver, C. S., 1985, Forecasts and predictions of eruptive activity at Mount St. Helens, USA—1975–1984: Journal of Geodynamics, v. 3, no. 3/4, p. 397-423.

*Tilling, R. I., editor, 1989, Volcanic hazards: American Geophysical Union; International Geological Congress, 28th, Short Course in Geology, v. 1, 123 p.

Cascade Range

Bacon, C. R., 1983, Eruptive history of Mount Mazama and Crater Lake Caldera, Cascade Range, U.S.A.: Journal of Volcanology and Geothermal Research, v. 18, no. 1-4, p. 57-115.

Crandell, D. R., 1989, Gigantic debris avalanche of Pleistocene age from ancestral Mount Shasta volcano, California, and debris-avalanche hazard zonation: U.S. Geological Survey Bulletin 1861, 32 p.

Crandell, D. R.; Hoblitt, R. P., 1986, Lateral blasts at Mount St. Helens and hazard zonation: Bulletin of Volcanology, v. 48, no. 1, p. 27-37.

Crandell, D. R.; Waldron, H. H., 1973, Volcanic hazards in the Cascade Range. *In* Tank, R. W., editor, Focus on environmental geology: Oxford University Press, p. 19-28.

Crandell, D. R.; Mullineaux, D. R.; Miller, C. D., 1979, Volcanic-hazards studies in the Cascade Range of the western United States. *In* Sheets, P. D.; Grayson, D. K., editors, Volcanic activity and human ecology: Academic Press, p. 195-219.

Driedger, C. L.; Kennard, P. M., 1986, Ice volumes on Cascade volcanoes—Mount Rainier, Mount Hood, Three Sisters, and Mount Shasta: U.S. Geological Survey Professional Paper 1365, 28 p., 6 pl.

Harris, S. L., 1986, The other Cascade volcanoes—Historic eruptions at Mount St. Helens' sister peaks. *In* Keller, S. A. C., editor, Mount St. Helens—Five years later: Eastern Washington University Press, p. 20-33.

Harris, S. L., 1988, Fire mountains of the West—The Cascade and Mono Lake volcanoes: Mountain Press Publishing Company, 379 p.

*Hoblitt, R. P.; Miller, C. D.; Scott, W. E., 1987, Volcanic hazards with regard to siting nuclear-power plants in the Pacific Northwest: U.S. Geological Survey Open-file Report 87-297, 196 p., 5 pl.

Norris, R. D., 1991, The Cascade volcanoes—Monitoring history and current land management: U.S. Geological Survey Open-File Report 91-31, 89 p.

Richardson, Donald, 1968, Glacier outburst floods in the Pacific Northwest: U.S. Geological Survey Professional Paper 600-D, p. D79-D86.

Weaver, C. S.; Norris, R. D.; Jonientz-Trisler, Chris, 1990, Results of seismological monitoring in the Cascade Range, 1962–1989–Earthquakes, eruptions, avalanches, and other curiosities: Geoscience Canada, v. 17, no. 3, p. 158-162.

Glacier Peak

Beget, J. E., 1981, Postglacial eruption history and volcanic hazards at Glacier Peak, Washington: University of Washington Doctor of Philosophy thesis, 192 p.

*Beget, J. E., 1982, Postglacial volcanic deposits at Glacier Peak, Washington, and potential hazards from future eruptions: U.S. Geological Survey Open-File Report 82-830, 77 p.

Beget, J. E., 1982, Recent volcanic activity at Glacier Peak: Science, v. 215, no. 4538, p. 1389-1390.

Beget, J. E., 1983, Glacier Peak, Washington—A potentially hazardous Cascade volcano: Environmental Geology, v. 5, no. 2, p. 83-92.

Beget, J. E., 1984, Tephrochronology of late Wisconsin deglaciation and Holocene glacier fluctuations near Glacier Peak, north Cascade Range, Washington: Quaternary Research, v. 21, no. 3, p. 304-316.

Mount Adams

Hildreth, Wes; Fierstein, Judy, 1985, Mount Adams—Eruptive history of an andesite-dacite stratovolcano at the focus of a fundamentally basaltic volcanic field. *In* Guffanti, Marianne; Muffler, L. J. P., editors, Proceedings of the workshop on geothermal resources of the Cascade Range: U.S. Geological Survey Open-File Report 85-521, p. 44-50.

Vallance, J. W., 1986, Late Quaternary volcanic stratigraphy on the southwestern flank of Mount Adams volcano, Washington: University of Colorado Master of Science thesis, 122 p.

Vallance, J. W., [in press], Postglacial lahars and potential hazards in the White Salmon River system on the southwest flank of Mount Adams, Washington: U.S. Geological Survey Bulletin.

Mount Baker

Cary, C. M.; Thompson, J. M. S.; Pringle, P. T., 1992, Holocene lahar deposits from Mount Baker volcano in Glacier Creek, North Cascades, Washington [abstract]: Geological Society of America Abstracts with Programs, v. 24, no. 5, p. 13.

Easterbrook, D. J., 1975, Mount Baker eruptions: Geology, v. 3, no. 12, p. 679-682.

Frank, D. G., 1983, Origin, distribution, and rapid removal of hydrothermally formed clay at Mount Baker, Washington: U.S. Geological Survey Professional Paper 1022-E, 31 p., 1 pl.

Frank, D. G.; Meier, M. F.; Swanson, D. A.; and others, 1977, Assessment of increased thermal activity at Mount Baker, Washington, March 1975–March 1976: U.S. Geological Survey Professional Paper 1022-A, 49 p.

Frank, D. G.; Post, A. S.; Freidman, J. D., 1975, Recurrent geothermally induced debris avalanches on Boulder Glacier, Mount Baker, Washington: U.S. Geological Survey Journal of Research, v. 3, no. 1, p. 77-87.

*Hyde, J. H.; Crandell, D. R., 1978, Postglacial deposits at Mount Baker, Washington, and potential hazards from future eruptions: U.S. Geological Survey Professional Paper 1022-C, 17 p., 1 pl.

Mount Hood

Cameron, K. A.; Pringle, P. T., 1986, Post-glacial lahars of the Sandy River basin, Mount Hood, Oregon: Northwest Science, v. 60, no. 4, p. 225-237.

Cameron, K. A.; Pringle, P. T., 1987, A detailed chronology of the most recent major eruptive history of Mount Hood, Oregon: Geological Society of America Bulletin, v. 99, no. 6, p. 845-851.

Cameron, K. A.; Pringle, P. T., 1991, Prehistoric buried forests of Mount Hood: Oregon Geology, v. 53, no. 2, p. 34-43.

*Crandell, D. R., 1980, Recent eruptive history of Mount Hood, Oregon, and potential hazards from future eruptions: U.S. Geological Survey Bulletin 1492, 81 p., 1 pl.

Mount Rainier

Crandell, D. R., 1963, Paradise debris flow at Mount Rainier, Washington: U.S. Geological Survey Professional Paper 475-B, p. B135-B139.

Crandell, D. R., 1963, Surficial geology and geomorphology of the Lake Tapps quadrangle, Washington: U.S. Geological Survey Professional Paper 388-A, 84 p., 2 pl.

Crandell, D. R., 1967, Volcanic hazards at Mount Rainier, Washington: U.S. Geological Survey Bulletin 1238, 26 p.

Crandell, D. R., 1969 [1970], Surficial geology of Mount Rainier National Park, Washington: U.S. Geological Survey Bulletin 1288, 41 p., 1 pl.

Crandell, D. R., 1971, Postglacial lahars from Mount Rainier volcano, Washington: U.S. Geological Survey Professional Paper 677, 75 p., 3 pl.

*Crandell, D. R., 1973, Map showing potential hazards from future eruptions of Mount Rainier, Washington: U.S. Geological Survey Miscellaneous Investigations Series I-836, 1 sheet, scale 1:250,000.

Crosson, R. S.; Frank, David, 1975, The Mt. Rainier earthquake of July 18, 1973, and its tectonic significance: Seismological Society of America Bulletin, v. 65, no. 2, p. 393-401.

Cullen, J. M., 1978, Impact of a major eruption of Mount Rainier on public service delivery systems in the Puyallup Valley, Washington: University of Washington Master of Urban Planning thesis, 195 p.

Driedger, C. L., 1988, Geology in action—Jökulhlaups on Mount Rainier: U.S. Geological Survey Open-File Report 88-459, 2 p.

Driedger, C. L.; Fountain, A. G., 1989, Glacier outburst floods at Mount Rainier, Washington State, U.S.A. *In* Wold, Bjorn, editor, Proceedings of the symposium on snow and glacier research relating to human living conditions: Annals of Glaciology, v. 13, p. 51-55.

Fiske, R. S.; Hopson, C. A.; Waters, A. C., 1963, Geology of Mount Rainier National Park, Washington: U.S. Geological Survey Professional Paper 444, 93 p.

Frank, D. G., 1985, Hydrothermal processes at Mount Rainier, Washington: University of Washington Doctor of Philosophy thesis, 195 p.

Moxham, R. M.; Crandell, D. R.; Marlatt, W. E., 1965, Thermal features at Mount Rainier, Washington, as revealed by infrared surveys: U.S. Geological Survey Professional Paper 525-D, p. D93-D100.

Mullineaux, D. R., 1974, Pumice and other pyroclastic deposits in Mount Rainier National Park, Washington: U.S. Geological Survey Bulletin 1326, 83 p.

Mullineaux, D. R.; Sigafoos, R. S.; Hendricks, E. L., 1969, A historic eruption of Mount Rainier, Washington: U.S. Geological Survey Professional Paper 650-B, p. B15-B18.

National Research Council, 1994, Mount Rainier—Active Cascade volcano: National Academy Press, 114 p.

Pringle, P. T.; Palmer, S. P., 1992, Liquefiable volcanic sands in Puyallup, Washington correlate with Holocene pyroclastic flow and lahar deposits in upper reaches of the Puyallup River valley [abstract]: Geologic Society of America Abstracts with Programs, v. 24, no. 5, p. 76.

*Scott, K. M.; Pringle, P. T.; Vallance, J. W., 1992, Sedimentology, behavior, and hazards of debris flows at Mount Rainier, Washington: U.S. Geological Survey Open-File Report 90-385, 106 p., 1 pl. [To be released as U.S. Geological Survey Professional Paper 1447-C.]

Scott, K. M.; Vallance, J. W.; Pringle, P. T., [in press], Debris flows, debris avalanches, and floods, at, and downstream from Mount Rainier, Washington: U.S. Geological Survey Open-File Report 92-654.

Swanson, D. A.; Malone, S. D.; Samora, B. A., 1992, Mount Rainier—A Decade Volcano: Eos (American Geophysical Union Transactions), v. 73, no. 16, p. 177, 185-186.

Swanson, D. A.; Malone, S. D.; Casadevall, T. J., 1993, Mitigating the hazards of Mount Rainier: Eos (American Geophysical Union Transactions), v. 74 , no. 12, p. 133.

Mount St. Helens

Collins, B. D.; Dunne, Thomas, 1988, Effects of forest land management on erosion and revegetation after the eruption of Mount St. Helens: Earth Surface Processes and Landforms, v. 13, no. 3, p. 193-205.

Crandell, D. R., 1987, Deposits of pre-1980 pyroclastic flows and lahars from Mount St. Helens volcano, Washington: U.S. Geological Survey Professional Paper 1444, 91 p., 1 pl.

Crandell, D. R.; Mullineaux, D. R., 1978, Potential hazards from future eruptions of Mount St. Helens volcano, Washington: U.S. Geological Survey Bulletin 1383-C, 26 p.

Foxworthy, B. L.; Hill, Mary, 1982, Volcanic eruptions of 1980 at Mount St. Helens—The first 100 days: U.S. Geological Survey Professional Paper 1249, 125 p.

Hoblitt, R. P., 1990, Current perspectives on the 18 May 1980 lateral blast deposit at Mount St. Helens, Washington [abstract]: Geoscience Canada, v. 17, no. 3, p. 126.

Lehre, A. K.; Collins, B. D.; Dunne, Thomas, 1983, Post-eruption sediment budget for the North Fork Toutle River drainage, June 1980–June 1981. *In* Okuda, S.; Netto, A.; Slaymaker, O., editors, Extreme land forming events: Zeitschrift für Geomorphologie, supplementband 46, p. 143-163.

Lipman, P. W.; Mullineaux, D. R., editors, 1981, The 1980 eruptions of Mount St. Helens, Washington: U.S. Geological Survey Professional Paper 1250, 844 p.

Manson, C. J.; Messick, C. H.; Sinnott, G. M., 1987, Mount St. Helens—A bibliography of geoscience literature, 1882–1986: U.S. Geological Survey Open-File Report 87-292, 205 p.

Mullineaux, D. R., 1986, Summary of pre-1980 tephra-fall deposits erupted from Mount St. Helens, Washington State, USA: Bulletin of Volcanology, v. 48, no. 1, p. 17-26.

Pallister, J. S.; Hoblitt, R. P.; Crandell, D. R.; Mullineaux, D. R., 1992, Mount St. Helens a decade after the 1980 eruptions—Magmatic models, chemical cycles, and a revised hazards statement: Bulletin of Volcanology, v. 54, no. 2, p. 126-146.

Pringle, P. T., 1993, Roadside geology of Mount St. Helens National Volcanic Monument and vicinity: Washington Division of Geology and Earth Resources Information Circular 88, 120 p.

Scott, K. M., 1988, Origins, behavior, and sedimentology of lahars and lahar-runout flows in the Toutle–Cowlitz River system: U.S. Geological Survey Professional Paper 1447-A, 74 p.

Scott, K. M., 1989, Magnitude and frequency of lahars and lahar-runout flows in the Toutle–Cowlitz river system: U.S. Geological Survey Professional Paper 1447-B, 33 p.

U.S. Forest Service, 1992, Mount St. Helens contingency plan 1992—Gifford Pinchot National Forest: U.S. Forest Service, 1 v.

Yamaguchi, D. K., 1983, New tree-ring dates for recent eruptions of Mount St. Helens: Quaternary Research, v. 20, no. 2, p. 246-250.

Miscellaneous References

Bolt, B. A.; Horn, W. L.; MacDonald, G. A.; Scott, R. F., 1977, Geological hazards—Earthquakes, tsunamis, volcanoes, avalanches: Springer-Verlag, 330 p.

Casadevall, T. J., 1992, Volcanic hazards and aviation safety: Federal Aviation Administration Aviation Safety Journal, v. 2, no. 3, p. 9-17.

Casadevall, T. J., 1993, Volcanic ash and airports—Discussions and recommendations from the Workshop on Impacts of Volcanic Ash on Airport Facilities: U.S. Geological Survey Open-File Report 93-518, 52 p.

Dunne, Thomas; Smith, J. D.; Wigmosta, M. S., 1983, Field evidence for the flow properties of the Toutle valley mudflows: U.S. Bureau of Reclamation, 2 sheets microfiche [146 p.]; U.S. National Technical Information Service PB 86-157138.

Ewert, J. W.; Swanson, D. A., 1992, Monitoring volcanoes—Techniques and strategies used by the staff of the Cascades Volcano Observatory, 1980–1990: U.S. Geological Survey Bulletin 1966, 223 p.

Eisbacher, G. H.; Clague, J. J., 1984, Destructive mass movements in high mountains—Hazard and management: Geological Survey of Canada Paper 84-16, 230 p.

Fairchild, L. H., 1985, Lahars at Mount St. Helens, Washington: University of Washington Doctor of Philosophy thesis, 374 p.

Fairchild, L. H., 1986, Quantitative analysis of lahar hazard. *In* Keller, S. A. C., editor, Mount St. Helens—Five years later: Eastern Washington University Press, p. 61-67.

Higgins, J. D.; Naik, Bijayananda; Mills, S. V.; Copp, Howard; Roberson, J. A., 1983, The mechanics of mudflows: Washington Water Research Center Report 51, 116 p.

Lopez, D. L.; Williams, S. N., 1993, Catastrophic volcanic collapse—Relation to hydrothermal processes: Science, v. 260, no. 5115, p. 1794-1795.

Norris, R. D., [in press], Seismicity of rockfalls and avalanches at three Cascade Range volcanoes—Implications for seismic detection of hazardous mass movements: Seismological Society of America Bulletin.

Nuhfer, E. B.; Proctor, R. J.; Moser, P. H., 1993, The citizens' guide to geologic hazards: American Institute of Professional Geologists, 134 p.

Palmer, S. P.; Pringle, P. T.; Shulene, J. A., 1991, Analysis of liquefiable soils in Puyallup, Washington: *In* Proceedings—Fourth International Conference on Seismic Zonation, Stanford, California, 1991: Earthquake Engineering Research Institute, v. 2, p. 621-628.

Stine, C. M., 1990, Annotated bibliography, volcano-deformation monitoring: U.S. Geological Survey Open-File Report 90-47, 29 p.

Tanaka, Janet, 1986, The other side of the volcano—Social aspects of volcanic activity: Volcano News, no. 25/26, p. 1-8.

Wigmosta, M. S., 1983, Rheology and flow dynamics of the Toutle debris flows from Mount St. Helens: University of Washington Master of Science thesis, 184 p.

Wood, C. A.; Kienle, J., editors, 1990, Volcanoes of North America: Cambridge University Press, 354 p. ■

Growth Management Planning for Abandoned Coal Mines

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Although the damage from subsidence at abandoned coal mines has been relatively slight, there is potential for significant damage (Fig. 1) or serious injury. At least one cave-in was nearly disastrous. In 1967, a water-level tunnel collapsed in a newly terraced lot. Two children playing in the hole became unconscious from lack of oxygen. Their father and two policeman also passed out attempting to rescue the children. All were finally saved by firemen with oxygen equipment (Gilley and Collaizzi, 1970). Although the main problem was 'dead air' (lack of oxygen), physicians who treated the victims reported traces of methane in their lungs (Thorsen, 1987, *in* Walsh and Logan, 1989).

Abandoned coal mines underlie at least 50,000 acres in western and central Washington, in both rural and urban areas (Walsh and Logan, 1989). Additional acreage is affected by small mines and prospects for which there are no records. Outcrop and shallow subsurface geologic data are sufficient to estimate coal reserves for an area in Washington of approximately 250,000 acres (Fig. 2). Although most of this area is not underlain by mines or prospects, it represents the maximum potential extent of mines and prospects.

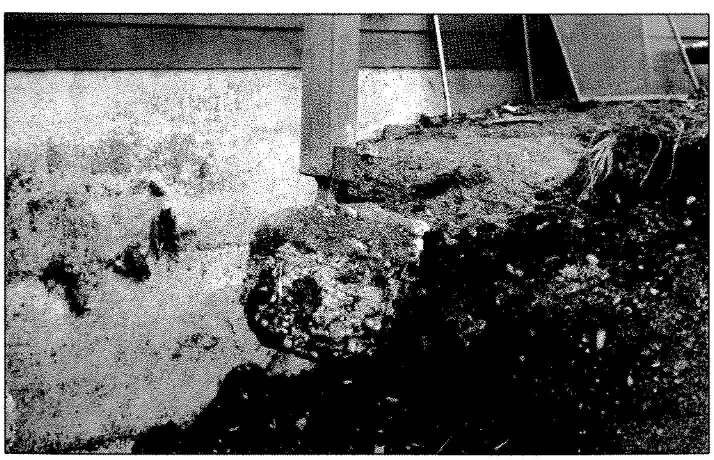

Figure 1. The footing for an outside staircase was left dangling when the ground surface collapsed in 1989 into the Waterhouse prospect south of Bellevue in King County.

King, Kittitas, Lewis, Pierce, Skagit, Thurston, and Whatcom Counties have had well-documented abandoned underground coal mines. In addition, there are numerous, poorly documented prospects in these counties as well as in Clark, Skamania, Cowlitz, Pacific, Snohomish, Clallam, Klickitat, Yakima, Asotin, Okanogan, Ferry, Stevens, Pend Oreille, and Spokane Counties.

Most jurisdictions are patterning their growth-management regulations after those of King County, which enacted a Sensitive Areas Ordinance in 1979. The basic element of the regulations is mapping of geologically hazardous areas coupled with requiring that applicants for building permits within these areas demonstrate the safety of the proposed project. King County requires that areas underlain by coal mines be made as safe as if no coal had ever been mined and suggests a horizontal buffer of 500 feet from the vertical projection of the mine, regardless of depth. Most other jurisdictions require either that the mined area be mitigated or that structures be engineered to tolerate some subsidence. Some jurisdictions, such as Pierce County, require that coal mine hazard mitigation be performed by an engineer, whereas most others permit geologists to do the work when appropriate.

Information Resources

Coal in Washington was first mined near Bellingham in 1853 (Beikman and others, 1961). In 1854, mines were opened near Renton and Issaquah, and by 1887, coal mining was a major industry in Washington Territory. Mines were operating in the Skagit River valley, near the towns of Roslyn and Cle

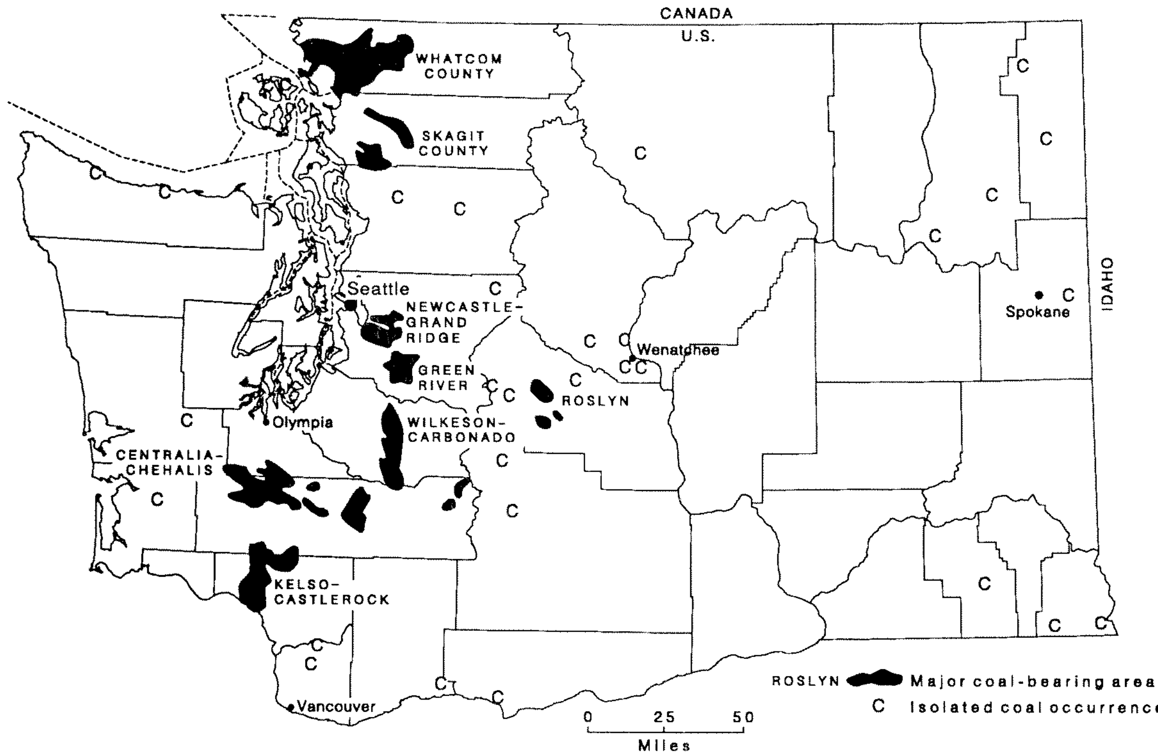

Figure 2. Major coal-bearing areas of Washington. (Modified from Beikman and others, 1961, and Halliday, 1963).

Elum in central Washington, in the vicinity of Black Diamond in King County, and near Wilkeson and Carbonado in Pierce County. In 1887, the first report about coal was published by the newly established office of the Territorial Mine Inspector. Initially, the powers of the office were limited, and it was not until the turn of the century that detailed mine maps began to be filed with the Mine Inspector. Eventually, all mine operators filed annual progress maps at a scale of 1 inch=100 feet.

This collection[1] of more than 900 maps is available for inspection at the office of the Washington Division of Geology and Earth Resources. However, we have no maps from the first half-century of the coal mining industry, when more than 20 million tons of coal were taken from underground mines.

Information about the location and condition of coal mines is necessary both to identify areas where abandoned coal mine hazards exist and to develop effective mitigation. These mine maps constitute an invaluable source of geological and engineering data to guide development in abandoned-mine areas, and they have been used to prepare detailed inventories of abandoned-mine lands for the Bellingham area (Tetra Tech, 1984), Renton (Morrison-Knudsen, 1985), Cougar Mountain near Bellevue (Skelly and Loy, 1985), Issaquah (Goodson and Associates, 1984), the Roslyn–Cle Elum area (Walker and Shideler, 1984), and a reconnaissance inventory for the rest of the state (LaSalata and others, 1985).

REFERENCES CITED

Beikman, H. M.; Gower, H. D.; Dana, T. A. M., 1961, Coal reserves of Washington: Washington Division of Mines and Geology Bulletin 47, 115 p.

Gilley, J. E.; Collaizi, G. J., 1970, Investigation of coal mine subsidence problem at Issaquah, Washington: U.S. Bureau of Mines unpublished report, 14 *l.*

Goodson and Associates, Inc., 1984, Abandoned coal mine survey in the area of Issaquah, King County, Washington: U.S. Office of Surface Mining Reclamation and Enforcement under contract to Goodson and Associates, Inc. [Denver, Colo.], 2 v., 8 pl.

Halliday, W. R., 1963, Caves of Washington: Washington Division of Mines and Geology Information Circular 40, 132 p.

La Salata, F. V.; Menard, M. C.; Walsh, T. J.; Schasse, H. W., 1985, Inventory of abandoned coal mines in the State of Washington: Washington Division of Geology and Earth Resources Open File Report 84-6, 42 p., 4 pl.

Morrison-Knudsen Company, Inc., 1985, Engineering investigation for the Renton, Washington area: U.S. Office of Surface Mining Reclamation and Enforcement under contract to Morrison-Knudsen Company, Inc. [Boise, Idaho], 87 p., 8 pl.

Skelly and Loy, 1985, Abandoned coal mine land survey, Coal Creek, King County, Washington: U.S. Office of Surface Mining Reclamation and Enforcement under contract to Skelly and Loy [Harrisburg, Penn.], 3 v., 2 pl.

Tetra Tech, Inc., 1984, Final Report—Bellingham abandoned mine land survey: U.S. Office of Surface Mining Reclamation and Enforcement under contract to Tetra Tech, Inc. [Englewood, Colo]., 33 p., 7 pl.

Walker, C. W.; Shideler, J. C., 1984, Abandoned coal mine hazards in the Roslyn coal field, Kittitas County, Washington; Final report: U.S. Office of Surface Mining Reclamation and Enforcement under contract to George E. Maddox and Associates [Spokane, Wash.], 3 v., 5 envelopes of maps.

Walsh, T. J; Logan, R. L., 1989, Land subsidence in Washington. *In* Galster, R. W., chairman, Engineering geology in Washington: Washington Division of Geology and Earth Resources Bulletin 78, v. I, p. 121-134. ■

[1] The collection is now available from the State Archives on five reels of microfilm. (The catalog is available from the Division of Geology and Earth Resources as Open File Report 94-7. If you wish to order microfilm, contact the Division. See page 2 of this issue.)

Revision to the 1994 Uniform Building Code Seismic Zone Map for Washington and Oregon

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In the last decade, several geological and geophysical studies have reshaped our understanding of earthquake sources in western Washington. We now recognize that the Cascadia subduction zone has the potential for generating great (magnitude 8 or larger) earthquakes with a return period averaging approximately 500–600 years. Additionally, studies of seismicity along the Mount St. Helens Fault Zone and in the Portland Basin have indicated that the potential for damaging crustal earthquakes may have been previously underestimated.

In response to this heightened understanding of the earthquake potential in western Washington, the Washington State Seismic Safety Advisory Committee (SSAC) recommended review of the current Uniform Building Code (UBC) seismic zone boundaries. The UBC is developed by the International Council of Building Officials (ICBO) as their recommended minimum code to govern new building construction; sections of the code may be updated yearly, and a new version is released every three years. The UBC seismic design section includes a map that divides the United States into six zones representing the expected severity of ground shaking. Seismic zone 4 assigns the highest level of design ground motion and outlines seismically active areas such as southern Alaska and along the San Andreas fault in California. At present the Puget Sound region is in seismic zone 3, and the rest of Washington is included in zone 2B (Fig. 1).

In response to the new information about earthquake sources and the SSAC policy plan, the Structural Engineers Association of Washington (SEAW) held a working session to consider seismicity and seismic zoning in January 1992. The session was organized by James E. Carpenter and John D. Hooper, respectively the chairmen of the Emergency Preparedness Committee and Lateral Forces Committee of SEAW. Participants included seismologists, geologists, and engineers from the University of Washington, U.S. Geological Survey, Washington Department of Natural Resources, Washington Department of Transportation, and members of structural and geotechnical engineering consulting firms practicing in Washington. The chairman of the Oregon Seismic Safety Policy Advisory Committee also attended the meeting.

As a result of the interdisciplinary exchange of information, the working group unanimously concluded that the area presently included in zone 3 should be expanded to include all of Washington west of the Cascade crest. The remaining eastern portion of the state would remain in seismic zone 2B (Fig. 1). The group also recommended that any proposed code changes be coordinated with the Structural Engineers Association of Oregon in order to produce a seamless version of the proposed zonation map. These recommendations were accepted by SEAW, and in July 1992 a code change submittal was forwarded to the ICBO for inclusion in the 1994 version of the UBC. The proponents for this submittal were the Structural Engineers Associations of Washington and Oregon, Oregon Seismic Safety Policy Advisory Committee, Oregon Department of Geology and Mineral Industries, and the Washington Department of Natural Resources.

In February 1993, the Code Development Committee of the ICBO approved consideration of the proposed seismic code change. In June 1993, the ICBO completed its approval of the proposed code change after expiration of the comment period. The 1994 version of the UBC has now been published and released.

The UBC must now be adopted by the state legislature before becoming the minimum building code standard for Washington. The Building Code Council, part of the Department of Community, Trade and Economic Development, is the lead agency for revisions to the State building code. The cycle of review for code revisions is as follows:

- A technical advisory committee holds public meetings regarding proposed changes coming from the 1994 UBC and makes recommendations to the Building Code Council;
- The Building Code Council holds public meetings and writes legislation that is proposed to the 1995 Legislature;
- The Legislature holds committee meetings and hears public comments and passes the final version of the State building code.

The newly revised State building code, likely but not necessarily including the new seismic zone 3 boundaries, will become the minimum building code in Washington on July 1, 1995. ■

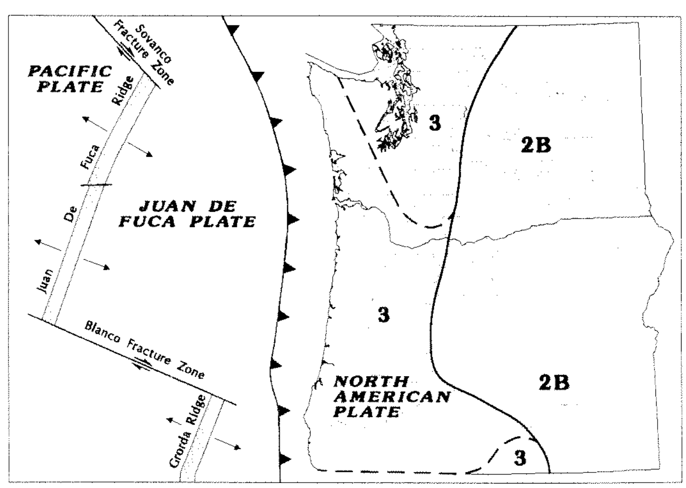

Figure 1. 1994 UBC seismic zones 2B–3 boundary (solid) and the previous 2B–3 boundary (dashed except where coincident with the 1994 version.)

Aspects of Growth Management Planning for Mineral Resource Lands

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INTRODUCTION

In this article, we briefly assess statewide progress in implementing the Growth Management Act as it relates to mineral resources. We describe geologic and other constraints on the availability of minerals, review the environmental impacts of mining, and offer some suggestions for the comprehensive planning process. Included are suggested volumes and sizes of mineral deposits that could be designated by local governments as part of the planning process for the Growth Management Act.

THE GROWTH MANAGEMENT ACT

The Washington Growth Management Act (Revised Code of Washington [RCW] 36.70A) requires county and municipal governments to undertake comprehensive land-use planning designed to balance the numerous and seemingly conflicting goals of good public policy. While the Act mandates environmental protection and maintenance of our high quality of life, it also directs local governments to plan for improved public transportation systems and increased availability of low-cost housing. Low-cost housing and public works depend on ready access to inexpensive sand, gravel, and crushed rock that cannot be extracted without social and environmental costs. In laypersons' terms, local governments are being asked to determine whether mining "in our backyards" will have fewer detrimental impacts than artificially limiting the mineral supply or mining in remote or environmentally sensitive areas. The answers aren't obvious, nor is one set of answers applicable to all counties, cities, and towns. The Act encourages local governments to plan for sustainable economic growth, that is, continuous economic development that never exceeds the capacity of the land, environment, or community to sustain that growth.

In order to balance their planning goals, local governments must map and designate mineral resources of long-term commercial significance. Generally, these resources will have the lowest environmental, social, and economic costs. Designation identifies key mineral resources so these can be protected from conflicting land uses with a set of Development Regulations (RCW 36.70A.060). The Department of Community Development (now the Department of Community, Trade and Economic Development) has written rules to implement the Act that direct local governments to classify both *existing and potential* mineral deposits (Washington Administrative Code [WAC] 365-190-070(c)).

Each county that is required to produce a comprehensive plan under the Act has been given a State General Fund appropriation ranging from $70,000 to more than $200,000. These funds have been used by the counties and included towns to finance Growth Management planning.

IMPLEMENTING THE GROWTH MANAGEMENT ACT

After the Act was adopted in 1990, all local governments in the most populous counties, counties experiencing rapid population growth, and counties voluntarily subscribing to the requirements of the Act commenced research on mineral-resource issues. These counties, and cities in these counties, compiled detailed geologic maps in order to locate important deposits. Thurston County, for example, retained a consultant who worked closely with Department of Natural Resources personnel, local geologists, and others to produce a mineral overlay for the county growth management maps.

Many counties did not produce a detailed map of their mineral deposits. They chose to identify only those mines that are currently operating, have valid land-use determinations, and have Surface Mine Reclamation permits (issued by the Department of Natural Resources pursuant to RCW 78.44). Insufficient funding, a lack of appropriate expertise, or a perception that important minerals such as sand and gravel exist in abundance were reasons cited by counties that did not produce adequate mapping. In the past, at least one county reported that sand and gravel were present in such abundance that it was unnecessary to exploit good-quality deposits before permanent land development occurred. Today, accessible sand and gravel in this county is in short supply, and designating more than a 50-year resource would be difficult.

Following their initial efforts to identify deposits of long-term significance (RCW 36.70A.170), participating local governments designated some of these resources for protection under the Act. In some counties, protection under the Act means that mining is an approved land-use for designated lands, contingent on requisite zoning changes. For other local jurisdictions, designation means that the *option* to consider mining is sheltered by land-use regulations. (The authors favor the second approach because it gives local governments more flexibility to designate mineral resources lands.)

Mineral resource designation under the Growth Management Act does not reduce other environmental permitting requirements. For example, proposed mines that may discharge in an aquifer sensitive area require a National Pollutant Discharge Elimination System (NPDES) General Permit. This permit could not be issued without State Environmental Policy Act (SEPA) analysis, probably consisting of an Environmental Impact Statement.

Some regulations written as part of the Growth Management process have had the effect of restricting mining. Local governments imposed these restrictions because of the widely held opinion that reducing the supply of construction aggregates (sand, gravel, and crushed rock) would limit growth and avoid a continuous concrete cap over the Puget Lowland.

While this position may seem reasonable at first glance, it has several detrimental side effects. As noted above, regulations that limit mining markedly reduce the availability of low-cost housing and public works. The mineral industries create, support, or affect about one-fifth of the state's economy. Equally important is the fact that restrictive regulations do not diminish demand and therefore encourage mining of environmentally sensitive areas in adjacent counties, states, or countries that do not have comparable laws.

Other factors have hindered the mapping and regulation development processes. During the early phases of Growth Management planning, some participating local governments were deliberating controversial proposals for new mines. Naturally, community action groups opposed to these proposed mines viewed designation as the first step in mine approval and voiced concern about any proposed regulation that might relax the permitting process. The 1993 amendments to the Washington Surface Mining Act (RCW 78.44) added another complication. These amendments pre-empted local jurisdiction of reclamation by giving sole authority over reclamation to the Department of Natural Resources.

As a result of these factors, many counties chose to designate only those mineral resources that had existing conditional use permits and Surface Mine Reclamation permits. *Limiting designation to existing mines identifies only where minerals resources have been; it does not constitute a plan providing access to mineral resources for the future.*

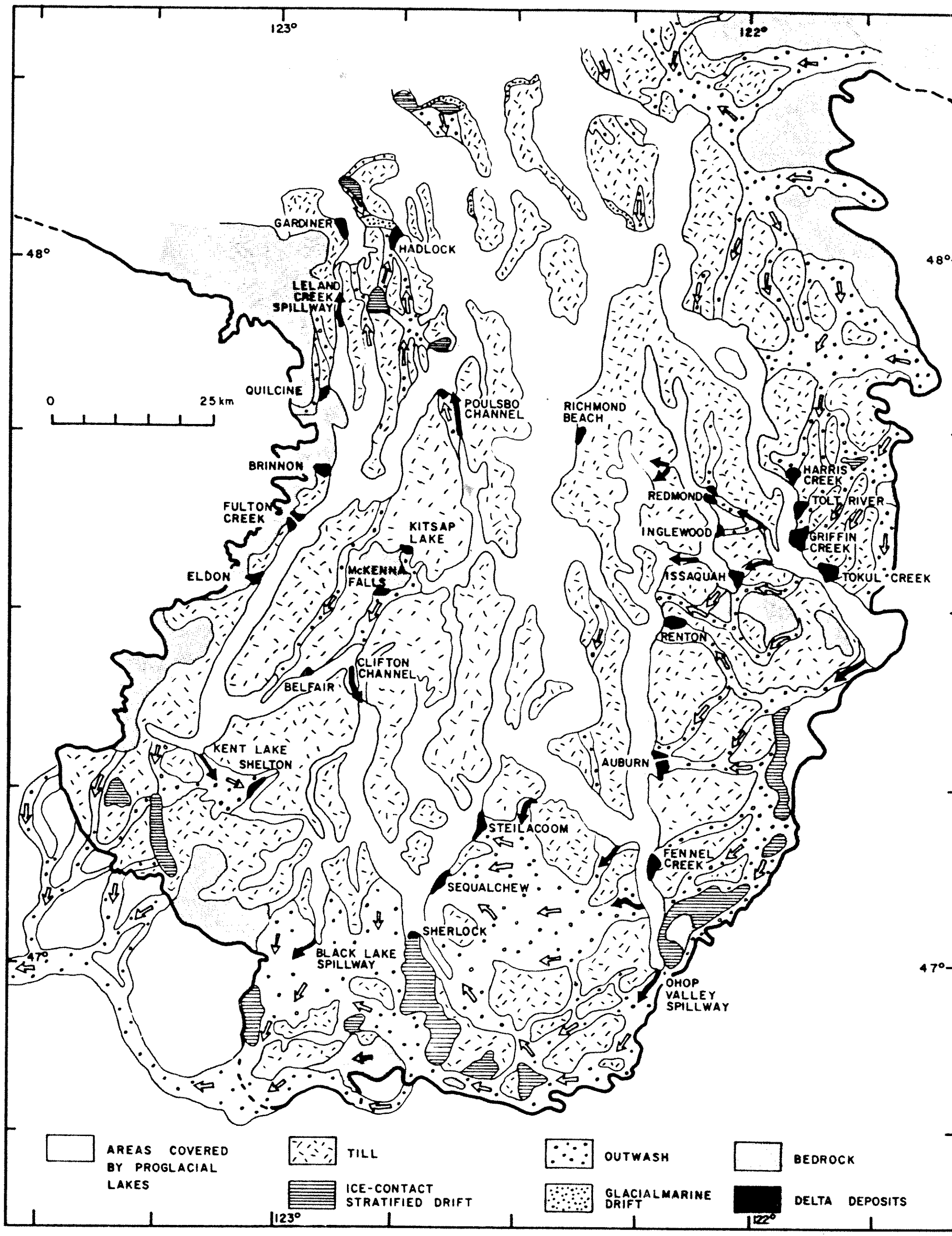

Figure 1. The distribution of some Pleistocene stratigraphic units related to retreat of the Puget lobe of the Cordilleran ice sheet. (From Thorson, 1980; reprinted with permission.) Glaciolacustrine deltas, many of which have been developed as giant sand and gravel mines, are shown in black. These relatively well sorted units are more than 150 feet thick. Glacial outwash sands and gravels, typically ranging from 25 to 100 feet thick, are stippled. The dashed pattern shows glacial tills, most commonly boulder clays that have no economic value. Open arrows indicate the orientation of inferred meltwater channels. The ancestral Chehalis River channel is in the extreme southwest corner of the map. Solid arrows indicate the direction of drainage from proglacial lake spillways. The heavy line indicates the maximum extent of the Puget lobe.

WASHINGTON'S MINERAL RESOURCES

Washington has an abundance of mineral resources, including important gold and magnesium mines and numerous giant sand and gravel mines. (See Fig. 1.) Currently, Washington has about 1,550 mines exclusive of borrow pits. Of the permitted private mines, 624 are sand and gravel pits (round rock aggregate) and 213 are quarries, which produce crushed aggregate and larger rock products such as riprap and jetty rock. Washington has ten clay mines, eight dolomite mines, and seven silica quarries (Lingley and Manson, 1992). Other mines produce diatomaceous earth, coal, and precious or base metals. (See Fig. 2.)

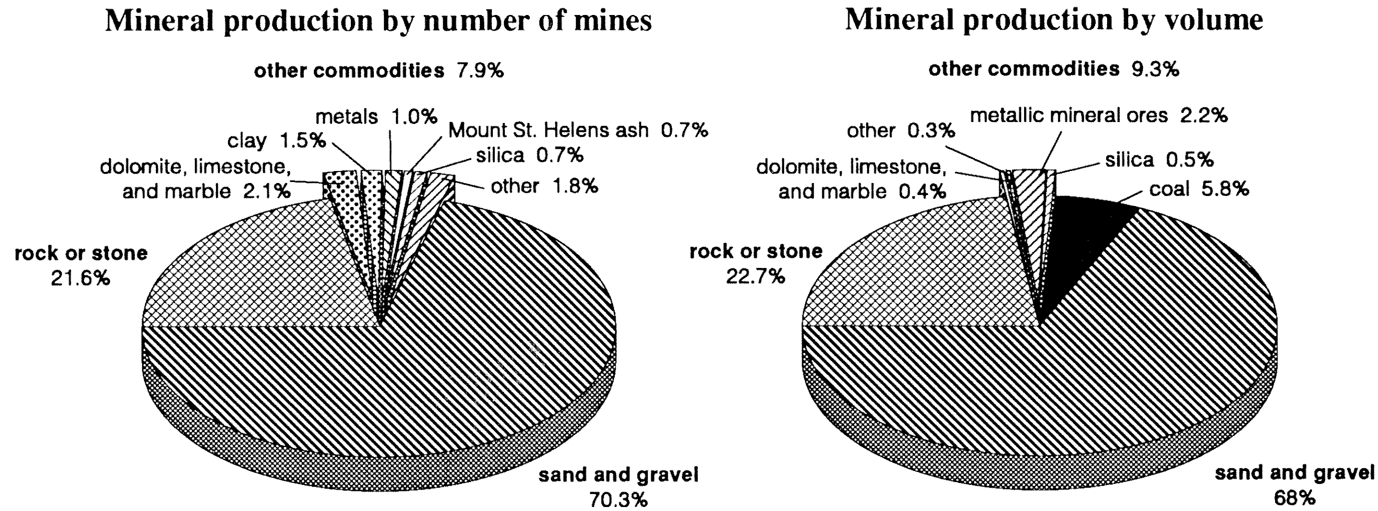

Figure 2. Washington's mineral resources by percentage of minerals or mineral ores produced. (From Lingley and Manson, 1992.)

The importance of mineral resources to public works is reflected in the large percentage of publicly owned mines; the Washington Department of Transportation, agencies of the federal government, and local governments own about 650 construction aggregate mines. Private industry owns approximately 900 mines. This abundance of mineral resources together with lively competition have contributed markedly to Washington's economy.

Except for sand, gravel, and bedrock mines, detailed planning and designation of Washington's other mineral resources fall outside the experience and expertise of local governments. Intense competition and international control over price characterize the metallic minerals business and inhibit industry from disclosing potential metallic mineral resources of long-term commercial significance. (Existing metallic and industrial mineral mines are listed in Lingley and Manson, 1992, and Derkey and Gulick, 1994).

THE GEOLOGY OF CONSTRUCTION AGGREGATES

Sand, gravel, and crushed rock are literally the foundation for each community's infrastructure. All construction and transportation projects are dependent on construction aggregates. The Puget lowlands from Thurston County northward to the Canadian border contain large quantities of sand and gravel. Hard and durable bedrock, suitable for use as crushed aggregate and larger rock products, is plentiful in the foothills of the central and northern Cascades. Southeastern Washington is covered by flood basalts that also make good-quality crushed aggregates. Spokane and the Tri-Cities have an abundance of gravel.

Most of Washington's large sand and gravel deposits are related to Pleistocene continental ice sheets, which covered the northern third of the state as recently as 15,000 years ago (Booth and Goldstein, 1994). These glacial deposits are widespread and yield aggregates of better quality than younger fluvial deposits. Late Pleistocene glaciers in Washington gouged relatively hard and durable rock, such as granodiorites and gneisses, from the mountains of British Columbia. Rapidly flowing streams issuing from the ice sheets transported and rounded the coarser sediments, which are now preserved in braided stream, kame terrace, and glaciolacustrine-deltaic deposits. These deposits contain small proportions of lithologies that are prone to rapid weathering (such as siliceous volcanic rocks) or are weak (layered metamorphic and sedimentary rocks).

A large percentage of Washington's gravel comes from thick, well-sorted, sand and gravel units deposited as deltas within glacially dammed lakes. The giant Tokul Creek, Issaquah, Auburn, and Steilacoom deposits are examples of glacial-deltaic environments (Fig. 1). Other thick deposits, such as those on South Hill near Puyallup, probably formed in depressions between the ice lobes and adjacent hills.

The southern boundaries of Thurston, Douglas, Ferry, and Stevens Counties mark the approximate limit of the advance of continental glaciers. Glacially derived sand and gravel deposits are less common, smaller, and sand rich in areas farther south. Consequently, much of southern Washington relies on relatively expensive quarried basalt or lower quality sand and gravel units deposited by the Snake, Columbia, Yakima, Lewis, and Chehalis Rivers.

A few large and important gravel resources related to glacial events formed in southern Washington at considerable distance from the ice front:

- The thick gravel deposits in Grays Harbor County were deposited by the ancestral Chehalis River. This river was the only escape for glacial meltwater flowing from the Puget lowlands because the northern part of the sound was dammed by the Puget lobe of the Cordilleran ice sheet. (Today's Chehalis River is too small, or "under-fit", for its wide valley.)
- In eastern Washington, the Spokane–Rathdrum Prairie Aquifer is developed in remarkably thick and coarse gravel units deposited during floods that occurred when the ice dams that formed glacial Lake Missoula collapsed.
- Gravel deposits at Richland and Pasco formed when these same Missoula flood waters were impeded and (or) dammed at Wallula Gap. (See Waitt, 1985.)

With respect to bedrock, high-quality "granitic" (actually, granodiorite and related intrusive rocks) and metamorphic units are mainly present in the northern half of the state (for example, the Snoqualmie, Index, and Colville batholiths).

Reasonably good quality Columbia River basalts are nearly ubiquitous in southeastern Washington, thus simplifying planning for quarried rock in those areas.

However, southwestern Washington and the Olympic Peninsula have a dearth of hard and durable bedrock. Quarried stone in southwest Washington typically consists of marine volcanic rocks that have poor strength and durability. Contact with sea water during extrusion of these lavas quickly formed structurally weak clay minerals and volcanic glass. A few subaerial basalt flows, most of which can be recognized by their columnar jointing, are important sources of high-quality bedrock. The Black Lake quarry in Tumwater is a typical example. Local deposits of the Columbia River Basalt Group in the lower Columbia and Chehalis River valleys provide some good-quality rock.

THE CONSTRUCTION AGGREGATE INDUSTRY

Construction aggregates are used in a variety of applications—ready mix concrete, asphalt (asphaltic concrete), preformed concrete products, road base, fill, railroad ballast, and various erosion-control products such as riprap, jetty stone, and armor stone. Characteristics of the construction aggregate business that affect growth management planning are:

- The volume of rock used in any market depends on the characteristics of the region, especially the population growth rate. However, every area has a basic ongoing annual requirement for construction aggregates, even those markets experiencing no population growth.
- Aggregate prices are sensitive to transportation costs. The price of rock, FOB the mine, is typically in the range of \$3.50 to \$5.00 per ton. Delivered cost of aggregate increases at a rapid rate as distance from the mine increases. In most urban areas, the costs of transportation exceed the value of the aggregate by a factor of two or more.
- Transportation per-ton-mile costs are typically about \$0.05 for barges, \$0.10 to 0.20 for trucks (White and others, 1990) and can be considerably higher for short-haul rail transport (reflecting higher loading and labor costs).
- Because of high transportation costs, aggregate producers primarily serve local markets. While the mine to market distance can vary dramatically depending on the location of competitors, most aggregate producers can only serve customers within a 20- to 30-mile haul radius of their mine or batch plant.
- Price is also sensitive to local geology. In areas such as Kitsap County, for example, many deposits contain large volumes of clay and sand that are too fine for most applications. In these areas, manufacturing aggregate products by crushing quarried bedrock can be less expensive than processing poor-quality gravel.
- Concrete producers commonly transport round rock aggregate long distances when a local source is unavailable. But wet concrete will begin to set if it is hauled for long periods. Consequently, batch plants are commonly sited close to the market.
- Ready mix concrete producers generally prefer gravel to crushed quarry stone because of its "workability" (the relative ease of producing a smooth surface) and ease of mixing with cement to form concrete. Some engineers are beginning to use crushed aggregate for concrete batching because crushed rock gives the concrete interlocking strength, which may, in turn, lead to lower life-cycle costs for roads and other applications.
- Asphaltic concrete is manufactured with crushed aggregate because at least three freshly split faces on each pebble are necessary for the asphalt to adhere well. Asphalt paving companies prefer gravel deposits with abundant "oversized" round rock (cobbles and boulders).
- Crushed ⅝-inch-minus aggregate is the bread and butter product of the industry. Crushed products manufactured from quarried bedrock typically cost \$0.50 to \$1.00 per ton more than equivalent products made by crushing round rock because of the expense in drilling and blasting bedrock.
- Round rock is in relatively short supply, whereas bedrock is generally abundant. Coarse sand, used in making both portland cement concrete and asphaltic concrete, is in short supply in some markets.
- Three 600-acre quarries mined to an average depth of 100 feet would supply the entire 20-year construction aggregate demand for a large county. (However, the environmental and fiscal impacts of transporting rock from only three quarries throughout a county would be onerous.)
- Over a period of decades, most construction aggregate markets evolve from a gravel-based supply to a quarried bedrock supply. Producers tend to exhaust sand and gravel deposits in their market area prior to quarrying stone sources for crushed aggregate. Virtually all markets have some stone quarries to supply larger rock products.
- New deposits are becoming increasingly difficult and costly to bring into production. The costs of exploration and obtaining requisite permits to open a new mine are now a significant barrier, especially for small businesses. The typical producer will try to maintain a pre-tax profit margin of \$0.75 to \$1.00 per ton after all expenses. The cost of an Environmental Impact Statement and other work necessary to permit a mine ranges from \$10,000 to more than \$3,000,000. For the latter, 3,000,000 tons, the equivalent of a moderately sized deposit, must be produced and months to years must pass before the mine begins to be profitable.
- While land-use restrictions increase costs to consumers and increase transportation impacts, these restrictions do not necessarily slow development. For example, the rapid population growth of Houston, Texas, during the 1970s was sustained by mines located more than 100 miles from the city.
- Finally, mining is an interim land-use. Mineral resource lands are now converted to beneficial uses following mining.

IMPACTS OF MINING

Reclamation

Aggregate production temporarily obliterates entire mine-site ecosystems, but this loss can be mitigated with carefully sequenced reclamation. Until the last decade, reclamation was not regarded as a key criterion for evaluating the merits of proposed mines. Some Environmental Impact Statements for new mines contained impractical, incomplete, or erroneous reclamation schemes. Despite general public knowledge of the importance of successional reforestation, this concept was not applied to mine reclamation. Agencies and even environmental groups demanded that a climax flora appear on the mine site immediately after the minerals were depleted.

Some mining proposals were approved only after the proponent agreed to forego exploiting the entire available resource at the proposed mine site. For example, miners were required to establish unnecessarily large setbacks, to arbitrarily limit the depth of excavation, or to excavate working faces at angles that could not be produced with existing earthmoving equipment. These practices led to development of unnecessary mines as replacements for the mines that had been prematurely closed. Each unnecessary mine represents progressively more disturbance of the land's surface.

Industry impetus, technology, and new laws are stimulating aggressive reclamation of mine sites (Lingley and Norman, 1991; Norman and Lingley, 1991; Norman, 1992; see also D. K. Norman, 1992, draft surface mine reclamation guide; available for inspection at the Division's Olympia office). Washington's minimum reclamation standards are now among the most stringent in the western United States. (See the RCW 78.44.141.) The initial phases of successional restoration of ecosystems are now completed within 2 years of cessation of mining in most mine segments. These standards result in establishing healthy plant/soil ecosystems within a decade or two after mining. While 20 years may seem to be a long time, it is an order of magnitude shorter than natural reclamation that followed catastrophic geologic events such as the Cordilleran glaciation in the Puget Lowland or the Electron Mudflow in Pierce County. Technology exists to shorten the time for mine reclamation, but implementation of such technology carries a high environmental price and hinders colonization of the site by a hardy pioneer flora.

Transportation

The effects of truck traffic are a primary concern in designating construction aggregate mines. Truck traffic, usually expressed in ton-miles, in any given market can vary dramatically in response to zoning and public works decisions, especially those relating to road construction standards. Consider the following examples to illustrate our points:

(1) In county "A", the planning department designates resources close to the market, and the public works department requires high-strength roads and bridges capable of carrying 33-ton belly-dump trucks. In this county, a 1,000,000-ton-per-year market is served by mine-site batch plants, and all sand and gravel mines are located an average of 5 miles from the end-use location. A typical 5-mile haul-radius in this county would result in about 300,000 miles of truck traffic and roads that will last an average of 40 years.

(2) County "B" fails to designate resources closer than 15 miles to the market and forces crushing and batch plants to be located another 5 miles from the mines. These plants are restricted to daylight hours. County "B" public works builds minimal-quality roads that have 7-year average life cycles. Its bridges cannot withstand repeated use by heavy trucks, so gravel is transported with 10-ton trucks.

Delivering the same volume of aggregates to the end-use locations in county "B" requires 13 times more truck traffic than county "A" (4,000,000 miles)! Road maintenance coupled with restricted hours of operation result in frequent road closures for wasteful resurfacing and road closures during commuter hours.

(3) City "C" is supplied mostly by barge. For the same 1,000,000-ton-per-year market, city "C" needs only 400 annual barge loads (although some rock is still transported by truck to its end use). Contrast this minor impact with those that would occur if city "C" were supplied by 33-ton trucks. If the mine is 2 hours from the city, supplying the market would require 30,303 annual trips using 38 separate trucks. This equates to 152 daily trips, 200 days per year! ("No Action Alternatives" presented in existing Environmental Impact Statements for barge-borne aggregate proposals did not consider impacts of fabricating and maintaining 33-ton trucks.)

Clearly, truck traffic, with its attendant hazards to persons and windshields, noise, dust, road-wear, pollution, and energy inefficiency, can be reduced by thoughtful comprehensive planning.

Mining in Rivers

The potential for river avulsion (rapid changes in the channel) is a concern not always addressed in the county/city Shoreline Process (RCW 90.58). The Yakima River, for example, moved several hundred feet in one night after it eroded the bank and flowed through an abandoned mine. Erosion in the new channel created much turbidity and endangered Interstate Highway 82. (See D. K. Norman, DGER, 1992, draft surface mine reclamation guide.)

Damage to river beds can be another major impact of mining. For example, mining below the river bed creates an underwater waterfall that migrates upstream as the river attempts to reach hydrologic equilibrium. Some people believe that rivers are currently carrying artificially coarse bed loads owing to increased runoff following land clearing. They reason that scalping mid-channel bars will reduce the probability of flooding. However, such mining changes the river-bed morphology and can destroy river-bed habitat. (Collins and Dunn, 1989, and Pauley and others, 1989, are interesting reading on this subject.)

Water Quantity and Quality

Possible reduction of the quantity of ground water is a major concern in new mines. On two occasions in the past, excavation accidentally breached the lateral or seat-seals of perched aquifers, causing loss of water supplies and other damage. The 1993 amendments to the Surface Mining Act require a detailed hydrologic analysis for any new mine. (However, accidents are not entirely preventable, even with closely spaced monitoring wells.)

Aquifer draw-down from gravel removal and water-table tilting resulting from excavation in lakes are almost never of sufficient magnitude to impact ground-water quantity.

Ground-water quality has been a pivotal issue for almost every proposed mine in the last ten years. Nearly all gravel mines are located in or above aquifers, but ground-water quality problems related to aggregate mining seldom impact the community or environment significantly.

While mines that breach the water table are sometimes thought of as "windows" to the aquifer, the opposite is generally true. Many, if not most lakes created in mines act as aquitards. The aquitard effect occurs because clay stirred up in the process of mining settles out in the pore spaces within the first few centimeters below the lake bottom. (See Durbec and others, 1987.) This clay forms a low-permeability seat-seal. Where separate excavations breach the same, continuously porous aquifer, forming multiple lakes, it is not unusual to observe a different water level and turbidity in each lake.

Sand and gravel deposits mimic some filtering systems used to cleanse municipal water of turbidity and many large pollutants. Authigenic clay in the deposit is very effective for adsorbing metals and other polluting cations. However, many negatively charged pollutants and highly soluble chemicals, such as benzene, are not filtered by sand and gravel.

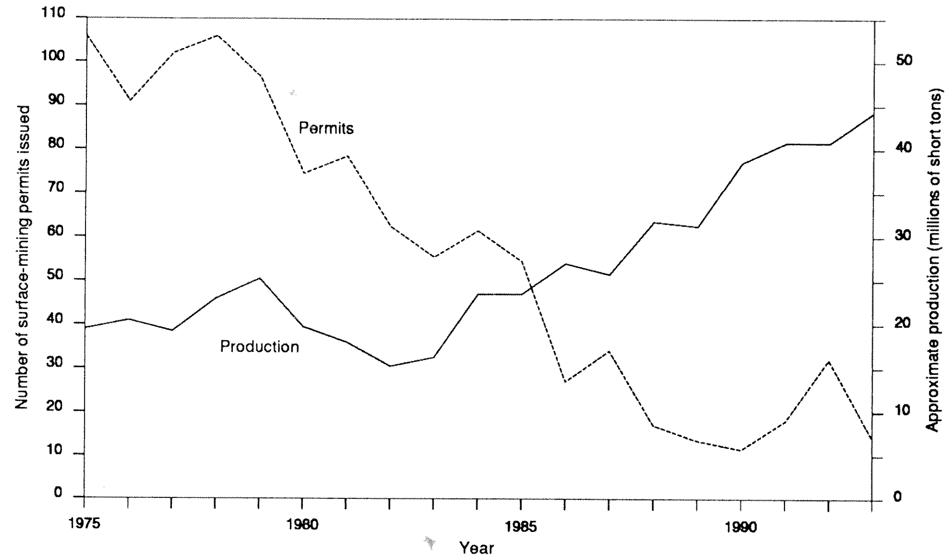

Figure 3. Round rock aggregate production and state surface mine reclamation permits by year. (Modified from Lingley and Manson, 1992, with additional production data from U.S. Bureau of Mines, 1993; 1994).

In contrast, consider excavations that penetrate the "A" soil horizon outside the mine. In most counties, the cumulative area of unsealed ditches, ground clearing, septic systems, and other excavations overlying aquifers is far greater than the cumulative disturbance from surface mining. Leaky automobile oil-pans and radiators that drain from parking lots and roads into porous soil generally cause more pollution than heavy equipment operation and maintenance in a mine.

Controlling all sources of pollution that could enter permeable ground is the only effective means of protecting aquifers.

Some local governments rely chiefly on dry vertical separation between pollution sources and ground water to protect the aquifer. While dry vertical separation can filter and kill coliform bacteria, it will not prevent introduction of more subtle pollutants. In these areas, zoning restrictions require mine-related excavation to stop a few feet above the aquifer. However, this practice may increase the risk to underlying waters as compared to excavations that create beneficial lakes. Factories and chemical plants are very rarely built on top of lakes, but these same, potentially polluting activities are easy to construct on dry land.

Another major detrimental impact related to mining that affects ground water is improperly backfilling sand and gravel pits with garbage. Bedrock quarries are commonly acceptable landfill sites but are seldom used as such.

Surface-water and ground-water quality is now addressed in a NPDES General Permit written by the Washington Department of Ecology that covers gravel mining.

Social Impacts

Detrimental social impacts of mining include noise, back-up alarms, blasting vibrations, glare, truck traffic, dust, and creation of attractive nuisances. Noise and air pollution commonly fall below the statutory definitions of infractions, but these can be acutely noticeable in pristine rural areas. Compounding these social impacts are the facts that miners sometimes provide rock for nighttime road repairs in order to minimize impacts to commuter traffic flow. Twenty-four hour and (or) early-morning concrete pours produce stronger products and are environmentally superior uses of the resource, but these activities can create a significant nuisance. The examples given in **Transportation** (see p. 40) above illustrate the benefit of designating mineral resource lands near end-use locations in order to reduce truck traffic impacts.

Berms and noise reduction technology and designating mineral resources in low-impact areas can markedly reduce mining impacts. Low-impact areas include industrial and commercial zones within the urban boundary where noise is masked by similar activities or where topography deflects noise. (A large percentage of noise travels along the line-of-sight.) The social impacts of mines in these locations can be significantly lower than those for mines in pristine rural parts of these same counties.

PLANNING

Providing continuous access to a minimal supply of construction aggregates is the chief mineral-resource problem facing growth management planners. Figure 3 illustrates the problem: during the past three decades gravel production has increased steadily. (Gravel production is directly proportional to gravel demand because processed aggregate is not stockpiled or stored for long periods.) During the 1980s and 1990s, the amount of accessible gravel in the Puget Lowland has steadily diminished and the number of permits issued for new surface mines has also declined steadily.

The diminishing gravel supply results partly from depletion of Washington's giant deposits. Lone Star Northwest Inc.'s Steilacoom mine near Tacoma is currently the largest sand and gravel producer in the United States; it supplies most of Seattle's rock products at relatively low environmental and economic costs. Associated Sand and Gravel's Everett pit (Fig. 4) produces about 40 percent of all construction aggregates used in Snohomish County. Both of these mines will be essentially depleted within the next 4 years. The Redmond pit

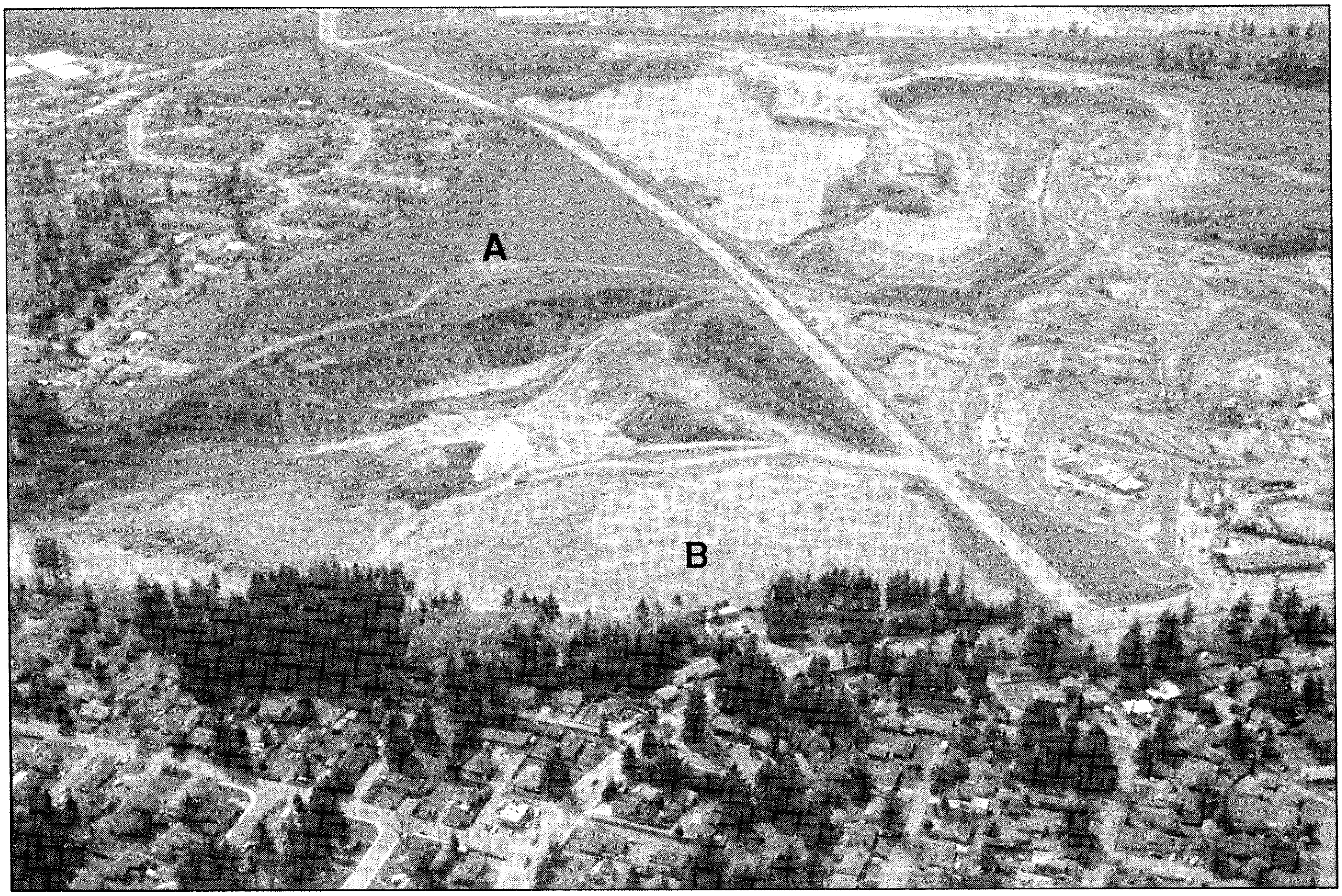

Figure 4. An aerial view to the west to the Associated Sand and Gravel, Inc., Everett pit. Since 1961 when this mine was in a near-rural setting, urban sprawl has brought single family residences with 50 feet of the southern highwall. The slopes near "A" were reclaimed in 1990, those near "B" are currently being reclaimed. (Photo courtesy of Art Hansen, Associated Sand and Gravel, Inc.).

(Cadman, Inc.), Cedar Shores pit (Stoneway Concrete Company), Friday Harbor pit (Friday Harbor Sand and Gravel, Inc.), and Fort Wright pit (Central Premix, Inc.) are essentially depleted. Failure to replace these resources will chill Washington's economy.

Most sand and gravel mines opened since 1980 are located in Vashon recessional outwash or recent fluvial deposits, both of which are thinner than the glacial deltaic gravel deposits. As a result, more mines and mines that disturb larger cumulative surface areas will be required to meet steadily increasing demand. Many of the remaining thick undeveloped gravel deposits lie in environmentally sensitive areas. These include deposits along Hood Canal, the Shelton delta, the Spokane–Rathdrum Prairie aquifer, and subaqueous deposits on the continental shelf in water depths of 80 to 300 feet. (Offshore deposits provide gravel for parts of Europe.) Many replacement resources cannot be exploited owing to conflicting land uses and, especially, urban sprawl. Both of these supply factors can be mitigated by thoughtful Growth Management planning.

Although replacement resources with relatively low environmental impact are still available close to population centers, many local governments have not been aggressive in locating these resources and protecting them from urban sprawl. Furthermore, it appears that some people favor exploiting deposits in environmentally sensitive areas, possibly because these deposits have few neighbors to offend. Mason County's experience is typical. A proposal to mine the Shelton delta is currently under consideration (Fig. 1). The delta is one of Washington's few undeveloped, giant, sand and gravel deposits. It is located near commercial and industrial areas, and the rock would be transported by a conveyor system beside an active rail line. However, the proposal has had considerable local opposition. Paradoxically, the most recent proposal to designate all of the large Hamma Hamma deposit in rural Mason County has received little opposition although the contiguous Hamma Hamma flood plain and Hood Canal are scenic resources of great importance.

The geological, engineering, and environmental criteria described above have a direct relation to good growth management planning. For example, it is clear from the shortage of high-quality bedrock resources southwest of Seattle that counties and cities in this area should designate all bedrock units that meet Washington Department of Transportation specifications for strength and durability.

Small deposits should also be designated as resources of long-term significance if no comparable resources are available. For example, subaerial basalts mined in the Kennedy Creek and Black Lake quarries are among few resources in Mason or Thurston Counties that can be used to produce high-quality large rock products. These quarries have been considered for designation.

Similarly, thoughtful mineral resource planning is especially important for Kitsap County. Kitsap County is impoverished with respect to coarse gravels and hard bedrock required to manufacture crushed aggregates, asphaltic concrete, or portland cement concrete. The county now pays 36 percent more than the statewide average for some construction aggregates (Lingley and Manson, 1992) because of the gravel shortage and costs of removing unusually large amounts of clay from the gravel. Bedrock of acceptable quality is available only at one deposit, which is located directly northwest of the naval ship yards in Bremerton.

SUGGESTIONS FOR A GOOD MINERAL RESOURCES COMPREHENSIVE PLAN

We suggest that comprehensive plans include the following elements:

Mapping

A detailed geologic map showing locations of all sand and gravel, hard and durable bedrock, industrial mineral, and metallic mineral deposits should be developed. This type of map is an excellent planning tool because it indicates the overall mineral wealth of the county, highlights mineral shortages, and shows mineral locations relative to other land uses. An accurate map can be used to judge new proposals for designation and to adjust for unanticipated growth that may require new resources.

A second map showing the locations of 20- and 50-year supplies of construction aggregates should also be developed and updated from time to time.

Designating Construction Aggregate Resources

Total per-capita annual demand in Washington is currently about 9 cubic yards of sand and gravel and 3 cubic yards of rock (Lingley and Manson, 1992). (These figures include all aggregate, commercial rock products, "borrow", forest road rock, and fill.) If demand continues unabated but the population does not increase, each Washingtonian will require about 240 cubic yards of construction aggregates during the next 20 years.

However, supply considerations indicate that markets of the future will increasingly rely on crushed bedrock. We anticipate that conservation and increasing production costs of rock products will reduce long-term gravel consumption.

As a result of these factors, we have the following suggestions for designating construction aggregate resources. Twenty-year designations might include 135 cubic yards of sand and gravel (if possible) and 81 cubic yards of hard and durable bedrock per person. This 20-year supply is predicated on the assumptions that during the next 20 years:

(A) *Total per capita consumption of all construction aggregates* will be reduced to about 90 percent of current levels (216 cubic yards per person). Conservation, recycling, increased cost, high-density development (which requires less rock per person), and political decisions will probably result in reduced demand despite continued population growth. (However, construction of mass transportation systems and other factors might increase demand.)

(B) *Per capita sand and gravel demand* will be reduced to 75 percent of current consumption because price increases resulting from supply shortages will shift the market to crushed bedrock. Even now, the most populous counties will have to designate all round-rock resources in order to meet the anticipated 50-year demand. (However, round rock from Alaska, Canada, or offshore deposits could supplant a gravel short fall.)

(C) *Quarried bedrock production* will offset the round rock shortage. We assume that the construction aggregate market will shift from round rock to crushed bedrock because bedrock suitable for quarrying is abundant in most counties. Furthermore, crushed rock is replacing some round rock because it can have superior interlocking strength.

In order to apply these suggestions, local governments should use projected 20- and 50-year average county/city populations.

While the Growth Management Act only requires designating a 20-year construction-aggregate supply, we encourage local governments to designate a 50-year supply in order to reduce land-use conflicts and to mitigate future aggregate shortages. As a minimum for 50-year designations, planners might assume a low average demand for construction aggregates of 80 percent of current levels and that the supply will continue to shift toward quarried products. Therefore, we suggest that the 50-year supply should include 240 cubic yards of sand and gravel and 240 cubic yards of quarried bedrock per person.

Rural counties with unusually large minerals resources that can be mined with minimal environmental impact and social concerns should designate larger volumes of aggregate and minerals. In these counties, mining contributes significantly to the economy and helps maintain the rural quality of life because, like forestry, designating lands for mining discourages subdivision and more intense development.

Historical bedrock resources, such as abandoned quarries at Index and Concrete, might be considered as sites for future mining.

The Department of Natural Resources recommends that individual construction aggregate resources having values greater than $5,000,000 should be designated (Lasmanis, 1990). U.S. Bureau of Mines (1994) estimates the value of sand and gravel is about $5.70 per cubic yard and crushed bedrock (stone) is $9.50 per cubic yard (based on 2.0 tons per cubic yard).

It is important to designate construction aggregate sources having lower values where specific materials are in short supply. For example, Grays Harbor County may wish to designate all locations where bedrock meets Washington Department of Transportation minimum specifications for strength and durability.

Recommended Designations for Other Minerals

In order to address metallic and industrial mineral resources, local governments should designate each mineral commodity source not nearing depletion that is listed in pages 62 through 76 of the Directory of Washington Mining Operations (Lingley and Manson, 1992). Proper designation of potential metallic and industrial mineral resources generally requires a geologist or mining engineer. If such expertise is unavailable within the county, local governments may seek information from the Department of Natural Resources, Division of Geology and Earth Resources.

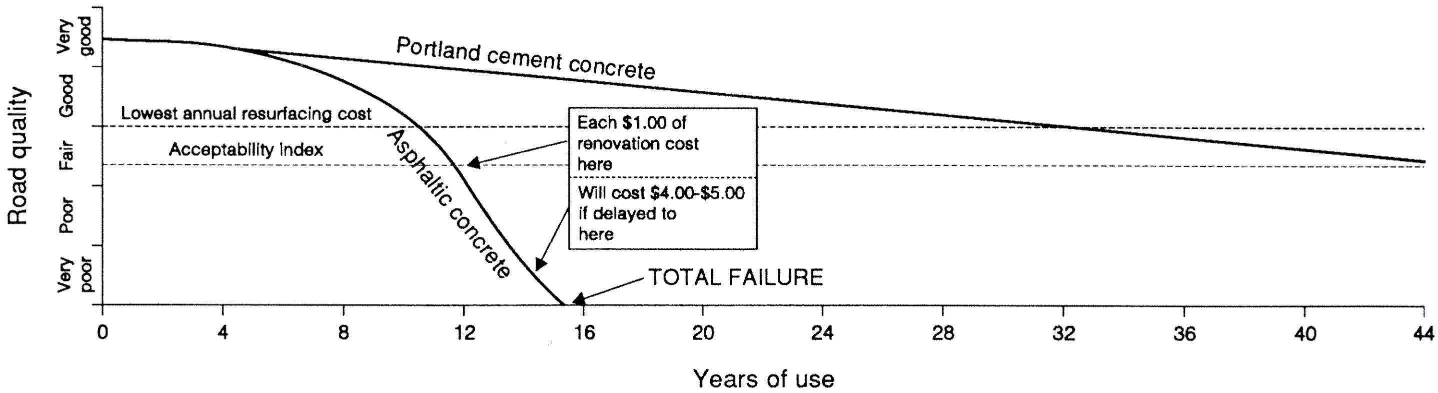

Figure 5. A comparison of some life-cycles for portland cement concrete and asphaltic concrete roads in Ontario, Canada. Although portland cement concrete is clearly preferable in this application, asphaltic concrete can be used to construct high-quality roads if properly engineered. (From Ready Mix Concrete Association of Ontario, 1988).

The Department suggests that industrial mineral and base or precious metal resources having values greater than $1,000,000 should be designated (Lasmanis, 1990). The value of these minerals should be determined using current commodity market prices.

Regulations

Regulations that protect the designated resources from conflicting land uses (RCW 36.70A.060) are the core of Growth Management. The Department of Natural Resources favors a two-tiered system:

(1) *Potential resources* are classified (WAC 365-190-070) and given limited protection.

The authors suggest that minimal protection consists of:

(a) notifying adjacent landowners located within 1,000 feet of designated resources, and

(b) zoning that allows for mineral *processing* and extraction, contingent upon favorable findings in a site-specific SEPA analysis.

(2) *Existing resources* of regional importance and those existing resources meeting the value criteria listed above should be designated and given full protection.

The authors suggest that full protection consists of thorough regulations allowing responsible operators to extract essentially all minerals from any given site before disturbing additional ground to develop a new mine. Such regulations might:

(a) Vest historical permitted mining uses such as crushing and batching,

(b) Follow carefully the process for Small Business Economic Impact assessments when developing or revising mining ordinances,

(c) Contain performance-based ordinances that are applicable to all other designated mineral resource sites within the county and attempt to achieve some consistency with those of adjoining counties.

(d) Develop ordinances that are direct and proportional to the impacts sought to be mitigated. For example, ordinances should limit impacts (noise and dust), but not activities (crushing and sorting).

(e) Provide that local approvals will be valid through completion of the subject surface mining. (Compliance should be achieved with fines, large if necessary, rather than shutdowns.)

(f) Assure that any changes to the "approved subsequent use" (RCW 78.44.031(1)) of the site remain compatible with mining activities.

(g) Notify adjacent landowners within 300 feet of the designated site.

(h) Develop zoning standards to protect buffers, especially those around quarries. (These will reduce flyrock risk and disturbance from ground vibration from blasting.)

Regulations should not be developed unless the local government has sufficient personnel to enforce the ordinances consistently and aggressively. Aggressive enforcement results in high levels of compliance but care must be taken to ensure that ordinances are uniformly administered.

Conservation Measures

Conservation of mineral resources is a key aspect of Growth Management that is generally overlooked. Most mineral resources are nonreplaceable without great amounts of energy and (or) ground disturbance. Those resources that industry values most for their low production costs and high quality are often the resources having the lowest associated environmental impacts. Clearly, these resources must be conserved.

Public works departments should be considered as key elements in Growth Management planning for mineral resource conservation because they are major consumers. Public works should implement (or, in some counties, maintain) development standards that optimize the life cycles of roads, bridges, and buildings. The volume of rock products consumed could be reduced by implementing standards that favor durability over low initial cost. Such standards can include improved road subbase preparation (better compaction), thicker road bases, reinforcement, and portland cement concrete surfaces for some applications. (See Fig. 5.) In Spokane, where freeze-thaw cycles are particularly hard on pavement, a concrete road has been in continuous use since 1910.

Recycling aggregates and aggregate products is also an important means of conservation. Portland cement concrete can be recycled easily for road base and other applications, provided that solid waste regulations do not prohibit or hinder industry's ability to store and process waste concrete. Worn out asphaltic concrete paving from roads that are being resurfaced can be continuously recycled directly into the hot asphalt mix.

Counties and cities planning under the Act are in a position to help develop the ideal blend of environmental protection, resource conservation, low-cost housing, and a sustainable economy.

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REFERENCES CITED

Booth, D. B.; Goldstein, Barry, 1994, Patterns and processes of landscape development by the Puget lobe ice sheet. *In* Lasmanis, Raymond; Cheney, E. S., convenors, Regional geology of Washington State: Washington Division of Geology and Earth Resources Bulletin 80, p. 207-218.

Collins, B. D.; Dunne, Thomas, 1990, Fluvial geomorphology and river-gravel mining—A guide for planners, case studies included: California Division of Mines and Geology Special Publication 98, 29 p.

Derkey, R. E.; Gulick, C. W., 1994, Washington's mineral industry—1993: Washington Geology, v. 22, no. 1, p. 3-15.

Durbec, A.; Ackerer, P.; Zilliox, L., 1987, Hydrodynamical exchanges between gravel pits and the aquifer—A risk for groundwater quality, field observations and modelling. *In* van Duijvenbooden, W.; van Waegeningh, H. G., editors, Vulnerability of soil and groundwater to pollutants—Proceedings and Information No. 38: National Institute of Public Health and Environmental Hygiene [The Hague], p. 1001-1009.

King County Department of Planning and Community Development, 1976, Extractive industries policy options: King County Department of Planning and Community Development, 56 p.

Lasmanis, Raymond, 1990, Growth Management Act of 1990 and mineral resource lands: Washington Geologic Newsletter, v. 18, no. 4, p. 2, 21-24.

Lingley, W. S., Jr.; Manson, C. J., 1992, Directory of Washington mining operations, 1992: Washington Division of Geology and Earth Resources Information Circular 87, 76 p.

Lingley, W. S., Jr.; Norman, D. K., 1991, Surface mining and surface mining law in Washington: Washington Geology, v. 19, no. 4, p. 38-48.

Norman, D. K., 1992, Reclamation of quarries: Washington Geology, v. 20, no. 4, p. 3-9.

Norman, D. K.; Lingley, W. S., Jr., 1992, Reclamation of sand and gravel mines: Washington Geology, v. 20, no. 3, p. 20-31.

Pauley, G. B.; Thomas, G. L.; Marino, D. A.; Weigand, D. C., 1989, Evaluation of the effects of gravel bar scalping on juvenile Salmonids in the Puyallup River drainage: University of Washington Cooperative Fishery Research Unit, 53 p.

Ready Mix Concrete Association of Ontario (Canada), 1988, Study for St. Catherines, Ontario, 8 p.

Thorson, R. M., 1980, Ice-sheet glaciation of the Puget Lowland, Washington, during the Vashon Stade (late Pleistocene): Quaternary Research, v. 13, no. 3, p. 303-321.

U.S. Bureau of Mines, 1993, The mineral industry of Washington in 1992: U.S. Bureau of Mines Mineral Industry Surveys, 4 p.

U.S. Bureau of Mines, 1994, The mineral industry of Washington in 1993: U.S. Bureau of Mines Mineral Industry Surveys, 4 p.

Waitt, R. B., 1985, Case for periodic, colossal jökulhlaups from Pleistocene glacial Lake Missoula: Geological Society of America Bulletin, v. 96, no. 10, p. 1271-1286.

White, W. W., III; Stebbins, S. A.; Hillman, Thomas, 1990, Puget Sound region sand and gravel market study: U.S. Bureau of Mines Report BIA 64-III, 149 p. ■

Contributions of the Division Library to Growth Management Planning

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The Growth Management Act requires local governments to classify and designate mineral resource lands and geologically hazardous areas within their jurisdictions. Maps and reports that describe these resources and hazards are essential sources of information from which to make wise management choices.

The kinds of reference materials that planners need are provided by the Division's library. In the past 100 years, more than 20,000 maps, reports, articles, and abstracts about Washington's geology have been issued. The Division collection includes all of these.

Some aspects of all this geologic literature make finding and using it a challenge. A good geologic library has to recognize that:

Some important materials are old. But geology is a cumulative science—observations made a century ago remain valid and are the stepping stones for new interpretations. New reports and maps do not automatically supersede the old.

Geologic information is produced by a mix of sources—federal, state, and local agencies, professional societies, research and commercial organizations. Masters and doctoral theses and field-trip guidebooks are other important sources. Some of these documents are considered to be "gray" literature, and traditional libraries find them difficult to deal with and may choose not to include them in collections.

Quantity and quality of geologic information are inconsistent. There may be 20 reports about one mine, but none on another; there may be a dozen detailed geologic maps of one area, but only a few small-scale reconnaissance maps of an adjacent area.

The Division library was established in 1935 in order to gather all kinds of reports and maps into one location and to make them available to the public. The library offers quick access to the 20,000+ known items. The staff constantly looks for and acquires new materials about Washington geology. The librarians can offer some literature resources that directly benefit planners. Among these are:

Geologic maps prepared by or for numerous organizations or institutions. The library has copies of all known geologic maps of the state from all known sources. We prepare annually updated bibliographies and indexes of mapping in Washington.

Bibliographies on selected topics. Recent bibliographies have been prepared on landslide, earthquake, and tsunami hazards.

Mining directories and mineral-resource inventories. Copies of Division reports of this type and those prepared by other agencies are in the library collection.

County bibliographies. Geologic and mineral-resource information has been compiled for 30 of Washington's 39 counties. These free bibliographies are available on paper or disk and are updated annually.

Bibliographic database. All library holdings are listed in the database, which is continuously updated. Bibliographies of acquisitions are issued for each calendar year and compiled as cumulations about every 5 years.

The Division library has a very extensive and well-indexed collection about Washington's geology, geologic hazards, and mineral resources. We encourage local planners, consultants, and other interested persons to use our library materials and expertise

Recently a consultant came to us for information about the hydrogeology of the Steilacoom area just south of Tacoma in Within minutes, we were able to put in his hands:

- the most recent geologic maps of the area
- the classic study of water resources of Pierce County
- a U.S. Geological Survey (USGS) report about the hydrogeology of the Tacoma area
- a 1986 consultant's report on the hydrogeology of the area
- a four-page list of reports on the hydrology of the Tacoma area, as printed from our in-house bibliography system.

We do not loan from our collection, so he could not borrow any of the materials from us. Instead, he copied a few of the short articles on the library's copier. We advised him how to borrow other materials from other libraries; most of the reports he needed could be borrowed from the Washington State Library a few blocks away. In an hour, this consultant found more information about the hydrogeology of the Steilacoom area than he could have found in a day anywhere else.

If he had had the time, and if it would have helped, we could also have done computer searches for him on our CD-ROM disks:

- GeoRef (1.6 million citations about international geology from 1785 to the present)
- USGS library (more than 100,000 books in the USGS library system, from 1971 to the present)
- GeoIndex (more than 20,000 geologic maps of the U.S.)
- Water Resources Abstracts (more than 100,000 books and papers about ground water and surface water)

The Division's library was established to help people get the information they need about the geology and mineral resources of Washington. We do whatever we can to make that happen.

The library is open during our regular business hours, 8:00 a.m. to 4:30 p.m., Monday through Friday. Please contact us at:
Phone: 206-902-1472
Fax: 206-902-1875
E-mail: Internet—cjmanson@u.washington.edu
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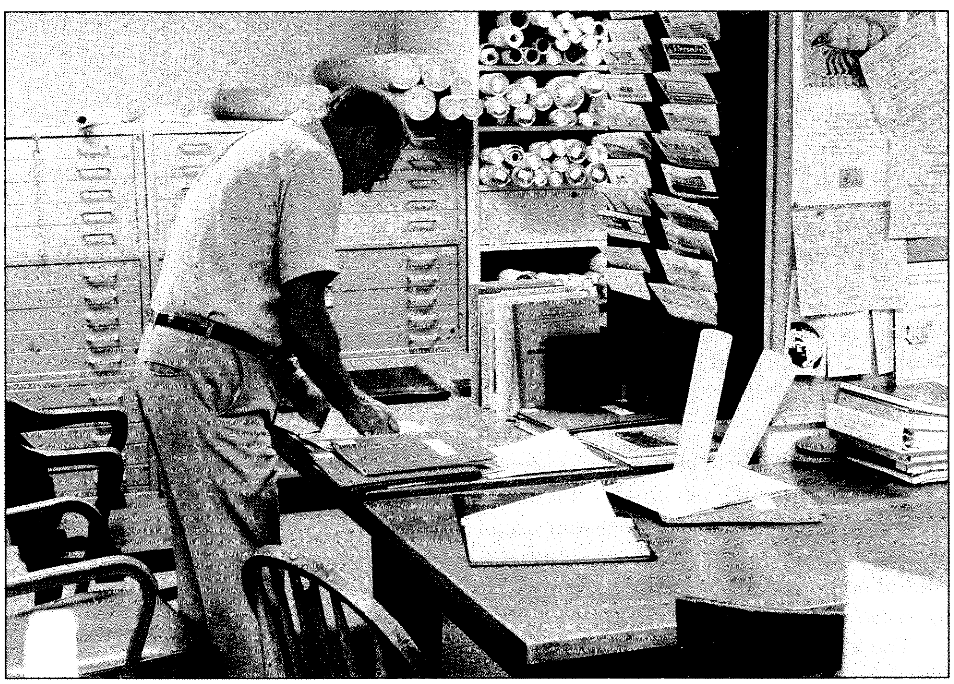

The DGER library collection contains more than 20,000 items (books, maps, articles and abstracts) on Washington's geology and more than 60,000 items on geology in general. It is heavily used by consultants (such as R. W. Galster, shown here) and educators as well as by the staffs of the Division and other local, state, and federal agencies. Note the map files and tubes and the stacked file of smaller newsletters in the background.

Selected Additions to the Library of the Division of Geology and Earth Resources

March 1, 1994, through June 30, 1994

THESES

Benoit, Paul, 1979, The man-induced topographic change of Seattle's Elliott Bay shoreline from 1852 to 1930 as an early form of coastal resource use and management: University of Washington Master of Marine Affairs thesis, 97 p.

Bream, S. E., 1987, Depositional environment, provenance, and tectonic setting of the upper Oligocene Sooke Formation, Vancouver Island, B.C.: Western Washington University Master of Science thesis, 228 p.

Choi, I. G., 1992, Chemical characterization of organic matter in temperate coniferous soil: University of Washington Doctor of Philosophy thesis, 90 p.

Durham, F. E., 1993, Geology and hydrogeology of eastern Lincoln County, Washington: Eastern Washington University Master of Science thesis, 204 p.

Graumlich, L. L., 1985, Long-term records of temperature and precipitation in the Pacific Northwest derived from tree rings: University of Washington Doctor of Philosophy thesis, 198 p.

Johnson, M. S., 1992, Hydrology and hydrogeology of Long Lake, Spokane and Stevens Counties, Washington: Eastern Washington University Master of Science thesis, 222 p.

Knoblach, D. A., 1994, A geological and historical summary of the Puget Group and Washington's stone industry, with a petrological and geochemical study of the Wilkeson Sandstone, Eocene Carbonado Formation: University of Puget Sound Bachelor of Science thesis, 231 p.

Lambeth, R. H., 1992, Hydrogeochemical characteristics of an unconsolidated aquifer downgradient from an oxidized, sulfidic mine tailings impoundment: Eastern Washington University Master of Science thesis, 140 p.

Rabbi, Fazli, 1992, Trace element geochemistry of polluted stream sediments and waters in Hunters and Cleveland areas of Stevens County, Washington: Eastern Washington University Master of Science thesis, 105 p.

Rieken, E. R., 1993, Active fault surface modeling using earthquake hypocenters—Applications to the Cascadia Benioff zone, Washington, and the 1989 Loma Prieta aftershock sequence, California: Washington State University Doctor of Philosophy thesis, 66 p.

Schultz, A. P., 1993, A 2-D velocity structure for a cross-Cascades profile using earthquake sources: University of Washington Master of Science thesis, 55 p.

Weigand, D. C., 1991, Effects of gravel scalping on juvenile salmonid habitat: University of Washington Master of Science thesis, 149 p.

U.S. GEOLOGICAL SURVEY

Arattano, M.; Savage, W. Z., 1992, Kinematic wave theory for debris flows: U.S. Geological Survey Open-File Report 92-290, 39 p.

Atwater, B. F., compiler, 1994, Geology of the Holocene liquefaction features along the lower Columbia River at Marsh, Brush, Price, Hunting, and Wallace Islands, Oregon and Washington: U.S. Geological Survey Open-File Report 94-209, 64 p.

Bliss, J. D., 1993, Modeling sand and gravel deposits—Initial strategy and preliminary examples: U.S. Geological Survey Open-File Report 93-200, 31 p.

Buchanan-Banks, J. M.; Collins, D. S., 1994, Map showing depth to bedrock of the Tacoma and part of the Centralia 30′ x 60′ quadrangles, Washington: U.S. Geological Survey Miscellaneous Field Studies Map MF-2265, 2 sheets, scale 1:100,000.

Carlson, D. H., 1993, Geology and geochemistry of the Coulee Dam Intrusive Suite and associated younger intrusive rocks, Colville batholith, Washington: U.S. Geological Survey Bulletin 1846, 36 p., 1 pl.

Casadevall, T. J., 1993, Volcanic ash and airports—Discussions and recommendations from the Workshop on Impacts of Volcanic Ash on Airport Facilities, Seattle, Washington, April 26–28, 1993: U.S. Geological Survey Open-File Report 93-518, 52 p.

Evarts, R. C.; Ashley, R. P., 1993, Geologic map of the Cowlitz Falls quadrangle, Lewis and Skamania Counties, Washington: U.S. Geological Survey Geologic Quadrangle Map GQ-1682, 1 sheet, scale 1:24,000, with 10 p. text.

Evarts, R. C.; Bishop, K. R., 1994, Chemical data for Tertiary volcanic and intrusive rocks of the Spirit Lake 15-minute quadrangle, southern Washington Cascade Range: U.S. Geological Survey Open-File Report 93-686, 24 p.

Fox, K. F., Jr.; Becraft, G. E., 1994, Geologic map of the Twin Lakes 15′ quadrangle, Ferry County, Washington: U.S. Geological Survey Open-File Report 93-715, 11 p., 2 pl.

Gardner, J. V.; and others, 1993, Map showing depth to basement in the deep-sea basins of the Pacific continental margin, Strait of Juan de Fuca to Cape Mendocino: U.S. Geologic Survey Miscellaneous Investigations Series Map I-2091-B, 1 sheet, scale 1:100,000.

Gardner, J. V.; and others, 1993, Map showing sediment isopachs in the deep-sea basins of the Pacific continental margin, Strait of Juan de Fuca to Cape Mendocino: U.S. Geologic Survey Miscellaneous Investigations Series Map I-2091-A, 1 sheet, scale 1:100,000.

Gough, L. P., compiler, 1993, Understanding our fragile environment—Lessons from geochemical studies: U.S. Geological Survey Circular 1105, 34 p.

Jacobson, M. L., compiler, 1994, National Earthquake Hazards Reduction Program, summaries of technical reports Volume XXXV: U.S. Geological Survey Open-File Report 94-176, 2 v. *Includes:*

Atwater, B. F., Holocene paleoseismology in western Washington State. Vol. I.

Ballantyne, D. B., Transfer of hazard information and assessment methods to water providers in the Pacific Northwest. Vol. II.

Booker, J. R., Electromagnetic remote sensing of structures controlling seismicity in the Puget Sound region. Vol. I.

Bucknam, R. C., Puget Sound paleoseismicity. Vol. I.

Crosson, R. S., Earthquake hazard research in the Pacific Northwest using Washington Regional Seismograph Network data. Vol. I.

Crosson, R. S.; Malone, S. D.; Qamar, A. I.; Ludwin, R. S., Washington Regional Seismograph Network operations. Vol. I.

Graves, R. W., Simulating the 3D basin response in the Portland and Puget Sound regions from large subduction zone earthquakes. Vol. II.

Jacoby, G. C.; Williams, P. L., Landslides in Lake Washington. Seattle—Coincidence intra-lake and correlation with regional seismic events. Vol. I.

Kulm, L. D.; Yeats, R. S.; Goldfinger, Chris, Cascadia subduction zone—Neotectonics of the continental shelf off Oregon and Washington. Vol. I.

Malone, S. D.; Crosson, R. S., Instrumentation to improve the Washington Regional Seismograph Network. Vol. II.

McCrory, P. A., Active margin tectonics, Pacific Northwest region. Vol. II.

Obermeier, S. F., Paleoseismic liquefaction studies—Coastal Washington State and Wabash Valley seismic zone. Vol. II.

Qamar, A. I.; Ludwin, R. S., Historic catalog. Vol. II.

Shennan, Ian; Innes, J. B.; Zong, Yongqiang; Long, Antony, A litho- and biostratigraphic evaluation of the coseismic subsidence and interseismic strain accumulation in the Washington and Oregon part of the Cascadia subduction zone. Vol. II.

Swanson, D. A., Influence of the southern Washington Cascades conductor on volcanism and tectonism. Vol. II.

Weaver, C. S., Regional seismotectonic studies. Vol. II.

Langer, W. H.; Glanzman, V. M., 1993, Natural aggregate—Building America's future: U.S. Geological Survey Circular 1110, 39 p.

Olhoeft, G. R.; Lucius, J. E.; Phillips, S. J., 1994, Geophysical tracking of the injection of trench stabilization materials at U.S. DOE Hanford site, Richland, Washington: U.S. Geological Survey Open-File Report 94-146, 77 p.

Payne, K. L.; Sumioka, S. S., 1994, Selected water-quality data for the Toppenish Creek basin, Yakima Indian Reservation, Washington: U.S. Geological Survey Open-File Report 93-486, 27 p., 1 pl.

Rinehart, C. D.; Fox, K. F., Jr., 1994, Geologic map of the Aeneas Valley quadrangle, Okanogan County, Washington: U.S. Geological Survey Open-File Report 93-709, 7 p., 2 pl.

Stanley, W. D.; Johnson, S. Y.; Nuccio, V. F., 1994, Analysis of deep seismic reflection and other data from the southern Washington Cascades: U.S. Geological Survey Open-File Report 94-159, 180 p.

Stover, C. W.; Coffman, J. L., 1993, Seismicity of the United States, 1568–1989 (revised): U.S. Geological Survey Professional Paper 1527, 418 p.

Swanson, R. D.; McFarland, W. D.; Gonthier, J. B.; Wilkinson, J. M., 1993, A description of hydrogeologic units in the Portland Basin, Oregon and Washington: U.S. Geological Survey Water-Resources Investigations Report 90-4196, 56 p., 10 pl.

Tabor, R. W.; Haugerud, R. A.; Booth, D. B.; Brown, E. H., 1994, Preliminary geologic map of the Mount Baker 30- by 60-minute quadrangle, Washington: U.S. Geological Survey Open-File Report 94-403, 55 p., 2 pl.

Vallier, T. L., 1994, Geologic hazards in the Hells Canyon region of Idaho, Oregon, and Washington: U.S. Geological Survey Open-File Report 94-213, 33 p.

Vallier, T. L.; Brooks, H. C., editors, 1994, Geology of the Blue Mountains region of Oregon, Idaho, and Washington: U.S. Geological Survey Professional Paper 1439, 198 p.

Yelin, T. S.; Tarr, A. C.; Michael, J. A.; Weaver, C. S., 1994, Washington and Oregon earthquake history and hazards: U.S. Geological Survey Open-File Report 94-226B, 9 p.

BOOKS ABOUT NORTHWEST GEOLOGY (etc.)

Association of Engineering Geologists, 1993, Geologic hazards and the Growth Management Act: Association of Engineering Geologists, 1 v. *Includes:*

Bailey, M. J., Subsidence due to abandoned coal mines.

Booth, D. B., Historical perspective—Growth and land use in western Washington.

Brunengo, M. J., Requirements of the Growth Management Act—Critical areas and resource lands.

Clark, Dave, Flood hazard regulations and the Growth Management Act.

Koloski, J. W., Growth management—The practical approach.

Laprade, W. T., Landslide hazards and the Growth Management Act.

McCormick, M. J., Status of current efforts in implementing the Growth Management Act.

Miller, L. R., Erosion hazards and Washington's Growth Management Act.

Noson, L. L., Seismic hazards and the Growth Management Act.

Pringle, P. T., Overview of volcanic hazards and growth management in Washington.

Barlow, D. P., 1993, Tsunami—Annotated bibliography; Version 2: British Columbia Ministry of Environment, Lands and Parks, Floodplain Management Branch, 36 p.

Barlow, D. P., 1993, Tsunami hazards—A background to regulation: British Columbia Ministry of Environment, Lands and Parks, Floodplain Management Branch, 48 p.

Doke, J. L.; Hashmi, G. S., 1994, Paradise Creek watershed characterization study: Washington Water Research Center Report 88, 271 p.

Franzen, Woody, 1994, Washington State aquatic lands teaching activities for middle and high school: Washington Division of Aquatic Lands, 1 v.

Geomatrix Consultants, Inc., 1993, Probabilistic seismic hazard analysis, DOE Hanford site, Washington: Westinghouse Hanford Company WHC-SD-W236A-TI-002, 1 v.

Lasmanis, Raymond; Cheney, E. S., convenors, 1994, Regional geology of Washington State: Washington Division of Geology and Earth Resources Bulletin 80, 227 p. *Contains:*

Atwater, B. F., Prehistoric earthquakes in western Washington.

Babcock, R. S.; Suczek, C. A.; Engebretson, D. C., The Crescent "terrane", Olympic Peninsula and southern Vancouver Island.

Booth, D. B.; Goldstein, B. S., Patterns and processes of landscape development by the Puget lobe ice sheet.

Brown, E. H.; Cary, J. A.; Dougan, B. E.; Dragovich, J. D.; Fluke, S. M.; McShane, D. P., Tectonic evolution of the Cascades crystalline core in the Cascade River area, Washington.

Busacca, A. J.; McDonald, E. V., Regional sedimentation of late Quaternary loess on the Columbia Plateau—Sediment source areas and loess distribution patterns.

Cheney, E. S., Cenozoic unconformity-bounded sequences of central and eastern Washington.

Cheney, E. S.; Rasmussen, M. G.; Miller, M. G., Major faults, stratigraphy, and identity of Quesnellia in Washington and adjacent British Columbia.

Cowan, D. S., Cordilleran tectonic setting of Washington.

Easterbrook, D. J., Chronology of pre-late Wisconsin Pleistocene sediments in the Puget Lowland, Washington.

Fox, K. F., Jr., Geology of metamorphic core complexes and associated extensional structures in north-central Washington.

Miller, F. K., The Windermere Group and Late Proterozoic tectonics in northeastern Washington and northern Idaho.

Miller, R. B.; Haugerud, R. A.; Murphy, Fred; Nicholson, L. S., Tectonostratigraphic framework of the northeastern Cascades.

Reidel, S. P.; Campbell, N. P.; Fecht, K. R.; Lindsey, K. A., Late Cenozoic structure and stratigraphy of south-central Washington.

Pauley, G. B.; Thomas, G. L.; Marino, D. A.; Weigand, D. C., 1989, Evaluation of the effects of gravel bar scalping on juvenile salmonids in the Puyallup River drainage; Draft: Washington Department of Fisheries, 53 p.

Peterson, C. D.; Darienzo, M. E.; Hamilton, Doann; Pettit, D. J.; Yeager, R. K.; Jackson, Philip; Rosenfeld, C. L.; Terich, T. A., 1994, Beach-shoreline database, Pacific Northwest region, USA: Oregon Department of Geology and Mineral Industries Open File Report O-94-2, 29 p., 1 diskette.

Scherrer, Wendy; Weisberg, Saul, editors, 1991, Living with mountains—A guide for learning and teaching about mountain landscapes: North Cascades Institute [Sedro-Woolley, Wash.], 252 p.

Shannon & Wilson, Inc.; Grant, H. P., 1993, Evaluation of liquefaction potential, Tacoma, Washington; Final technical report: Shannon & Wilson, Inc., 1 v.

University of Washington Geophysics Program, 1994, Quarterly network report 94-A on seismicity of Washington and western Oregon January 1 through March 31, 1994: University of Washington Geophysics Program, 33 p.

Washington Department of Ecology, 1994, Shoreline management guidebook, 2nd ed.; Volume I—Shoreline administrator's manual; Volume II—Shoreline master program handbook: Washington Department of Ecology.

Yorath, C. J., 1990, Where terranes collide: Orca Book Publishers [Victoria, B.C.], 231 p.

PAPERS

Ames, D. E.; Franklin, J. M.; Hannington, M. D., 1993, Mineralogy and geochemistry of active and inactive chimneys and massive sulfide, Middle Valley, northern Juan de Fuca Ridge—An evolving hydrothermal system: Canadian Mineralogist, v. 31, pt. 4, p. 997-1024.

Anton, W. F.; Polivka, R. M.; Harrington, Laurel, 1992, Seattle plays it safe: Civil Engineering (ASCE), v. 62, no. 8, p. 38-40.

Beckley, Darren, 1994, Benefits to wildlife from the reclamation of the Sherwood uranium mine: American Society for Surface Mining and Reclamation ASSMR Student Newsletter, Winter 1993–94, p. 1-3.

Benda, L. E.; Beechie, T. J.; Wissmar, R. C.; Johnson, A., 1992, Morphology and evolution of salmonid habitats in a recently deglaciated river basin, Washington State, USA: Canadian Journal of Fisheries and Aquatic Sciences, v. 49, p. 1246-1256.

Bigelow, P. K., 1994, Occurrence of a squaloid shark (Chondrichthyes—Squaliformes) with the pinniped *Allodesmus* from the upper Miocene of Washington: Journal of Paleontology, v. 68, no. 3, p. 680-684.

Blackwell, D. D., 1994, A summary of deep thermal data from the Cascade Range and analysis of the "rain curtain" effect: Oregon Department of Geology and Mineral Industries Open-File Report O-94-07, p. 75-131.

Bloomsburg, George, 1992, A groundwater management plan across a state boundary, Washington–Idaho. *In* Jones, M. E.; Laenen, Antonius, editors, Interdisciplinary approaches in hydrology and hydrogeology: American Institute of Hydrology, p. 389-397.

Branch, W. E., 1991, Hydrologic change caused by the eruption of Mount St. Helens. *In* Ritter, W. F., editor, Irrigation and drainage—Proceedings of the 1991 national conference: American Society of Civil Engineers, p. 531-538.

Brown, K. M.; Orange, D. L., 1993, Structural aspects of diapiric melange emplacement—The Duck Creek diapir: Journal of Structural Geology, v. 15, no. 7, p. 831-847.

Campbell, N. P.; Reidel, S. P., 1994, Further exploration for gas warranted in Columbia Basin: Oil and Gas Journal, v. 92, no. 18, p. 127-132.

Caruso, P.; Pareschi, M. T., 1993, Estimation of lahar and lahar-runout flow hydrograph on natural beds: Environmental Geology, v. 22, no. 2, p. 141-152.

Chin, C. S.; Coale, K. H.; Elrod, V. A.; Johnson, K. S.; Massoth, G. J.; Baker, E. T., 1994, In situ observations of dissolved iron and manganese in hydrothermal vent plumes, Juan de Fuca Ridge: Journal of Geophysical Research, v. 99, no. B3, p. 4969-4984.

Clague, J. J.; Bobrowsky, P. T., 1994, Evidence for a large earthquake and tsunami 100–400 years ago on western Vancouver Island, British Columbia: Quaternary Research, v. 41, no. 2, p. 176-184.

Cochrane, G. R.; Moore, J. C.; MacKay, M. E.; Moore, G. F., 1994, Velocity and inferred porosity model of the Oregon accretionary prism from multichannel seismic reflection data—Implications on sediment dewatering and overpressure: Journal of Geophysical Research, v. 99, no. B4, p. 7033-7043.

Connelly, B. A.; Cundy, T. W., 1992, Cumulative effects of forest management on peak streamflows during rain-on-snow events. *In* Jones, M. E.; Laenen, Antonius, editors, Interdisciplinary approaches in hydrology and hydrogeology: American Institute of Hydrology, p. 470-484.

Cowan, D. S.; Brandon, M. T., 1994, A symmetry-based method for kinematic analysis of large-slip brittle fault zones: American Journal of Science, v. 294, no. 3, p. 257-306.

Cowie, G. L.; Hedges, J. I., 1993, A comparison of organic matter sources, diagenesis and preservation in oxic and anoxic coastal sites: Chemical Geology, v. 107, no. 3-4, p. 447-451.

Crouse, C. B., 1994, Estimation of earthquake ground motions in the Pacific Northwest. *In* Applied Technology Council, Proceedings of seminar on new developments in earthquake ground motion estimation and implications for engineering design practice: Applied Technology Council, p. 16-1–16-5.

Dinehart, R. L., 1992, Evolution of coarse gravel bed forms—Field measurements at flood stage: Water Resources Research, v. 28, no. 10, p. 2667-2689.

Easthouse, K. B.; Spyridakis, D. E.; Welch, E. B., 1993, Aluminum chemistry in two pristine alpine lakes of the central Cascades, Washington: Water, Air, and Soil Pollution, v. 71, no. 3-4, p. 377-390.

Ebbesmeyer, C. C.; Tangborn, W. V., 1992, Linkage of reservoir, coast, and strait dynamics, 1936–1990—Columbia River basin, Washington coast, and Juan de Fuca Strait. *In* Jones, M. E.; Laenen, Antonius, editors, Interdisciplinary approaches in hydrology and hydrogeology: American Institute of Hydrology, p. 288-299.

Eliason, J. R., 1992, Analysis of the potential connection between the Roza aquifer and surface water in the Sinking Creek area in Lincoln County, Washington. *In* Jones, M. E.; Laenen, Antonius, editors, Interdisciplinary approaches in hydrology and hydrogeology: American Institute of Hydrology, p. 75-90.

Fountain, A. G., 1993, Geometry and flow conditions of subglacial water at South Cascade Glacier, Washington State, U.S.A; An analysis of tracer injections: Journal of Glaciology, v. 39, no. 131, p. 143-156.

Frankel, Arthur; Thenhaus, Paul; Perkins, David; Leyendecker, E. V., 1994, Ground motion mapping—Past, present and future. *In* Applied Technology Council, Proceedings of seminar on new developments in earthquake ground motion estimation and implications for engineering design practice: Applied Technology Council, p. 7-1–7-40.

Frost, Floyd; Frank, D. G.; Pierson, Kathy; Woodruff, Leigh; Raasina, Brent; Davis, Robert; Davies, Jac, 1993, A seasonal study of arsenic in groundwater, Snohomish County, Washington, USA: Environmental Geochemistry and Health, v. 15, no. 4, p. 209-214.

Garver, J. I.; Brandon, M. T., 1994, Fission-track ages of detrital zircons from Cretaceous strata, southern British Columbia—Implications for the Baja BC hypothesis: Tectonics, v. 13, no. 2, p. 401-420.

Gilmore, T. J.; Borghese, J. V.; Newcomer, D. R., 1993, Effects of river stage and waste water discharges on the unconfined aquifer, Hanford, Washington: Ground Water Monitoring and Remediation, v. 13, no. 1, p. 130-138,

Ginster, Ursula; Mottl, M. J.; Von Herzen, R. P., 1994, Heat flux from black smokers on the Endeavour and Cleft sediments, Juan de Fuca Ridge: Journal of Geophysical Research, v. 99, no. B3, p. 4937-4950.

Goodfellow, W. D.; Franklin, J. M., 1993, Geology, mineralogy, and chemistry of sediment-hosted clastic massive sulfides in shallow cores, Middle Valley, northern Juan de Fuca Ridge: Economic Geology, v. 88, no. 8, p. 2037-2068.

Goodfellow, W. D.; Grapes, Kate; Cameron, B. I.; Franklin, J. M., 1993, Hydrothermal alteration associated with massive sulfide deposits, Middle Valley, northern Juan de Fuca Ridge: Canadian Mineralogist, v. 31, pt. 4, p. 1025-1060.

Hanscom, J. C., 1994, Franklin and the Oregon Improvement Company—Company coal town: Columbia, v. 8, no. 1, p. 13-18.

Harr, R. D.; Coffin, B. A., 1992, Influence of timber harvest on rain-on-snow runoff—A mechanism for cumulative watershed effects. *In* Jones, M. E.; Laenen, Antonius, editors, Interdisciplinary approaches in hydrology and hydrogeology: American Institute of Hydrology, p. 455-469.

Harr, R. D.; Nichols, R. A., 1993, Stabilizing forest roads to help restore fish habitats—A northwest Washington example: Fisheries, v. 18, no. 4, p. 18-22.

Hassan, M. A.; Church, M. A., 1994, Vertical mixing of coarse particles in gravel bed rivers—A kinematic model: Water Resources Research, v. 30, no. 4, p. 1173-1185.

Hendry, J.; Armstrong, S.; Ring, T., 1992, Application of environmental isotopes to the study of groundwaters in the Toppenish Creek basin, Washington. *In* Jones, M. E.; Laenen, Antonius, editors, Interdisciplinary approaches in hydrology and hydrogeology: American Institute of Hydrology, p. 107-118.

Hershman, M. J., 1993, Critique of ocean policy in Washington State. *In* Wise, W. M., editor, Our coastal experience—Assessing the past, confronting the future: Coastal Society, International Conference, 12th, Proceedings, p. 19-27.

Heylmun, E. B., 1994, Placer gold in Washington: International California Mining Journal, v. 63, no. 6, p. 59-61.

Hohle, Janet, 1991, Geologic description of the Colville Reservation. *In* Manydeeds, S. A.; Smith, B. D., editors, Mineral frontiers on Indian lands: U.S. Bureau of Indian Affairs, p. 47-52.

Hoover, K. A.; Foley, M. G.; Heasler, P. G.; Boyer, E. W., 1991, Subgrid-scale characterization of channel lengths for use in catchment modeling: Water Resources Research, v. 27, no. 11, p. 2865-2873.

Howard, D. G., 1994, Strange heulandite crystals from Whitman Co., Washington: Microprobe, v. 7, no. 9, p. 19.

Jackson, C. R.; Cundy, T. W., 1992, A model of transient, topographically driven, saturated subsurface flow: Water Resources Research, v. 28, no. 5, p. 1417-1427.

Jarchow, C. M.; Catchings, R. D.; Lutter, W. J., 1994, Large-explosive source, wide-recording aperture, seismic profiling on the Columbia Plateau, Washington: Geophysics, v. 59, no. 2, p. 259-271.

Jirikowic, J. L.; Kalin, R. M., 1993, A possible paleoclimatic ENSO indicator in the spatial variation of annual tree-ring ^{14}C: Geophysical Research Letters, v. 20, no. 6, p. 439-442.

Keil, R. G.; Hedges, J. I., 1993, Sorption of organic matter to mineral surfaces and the preservation of organic matter in coastal marine sediments: Chemical Geology, v. 107, no. 3-4, p. 385-388.

Kelsey, H. M.; Bockheim, J. G., 1994, Coastal landscape evolution as a function of eustasy and surface uplift rate, Cascadia margin, southern Oregon: Geological Society of America Bulletin, v. 106, no. 6, p. 840-854.

Kerr, R. A., 1994, Throttling back the great lava floods?: Science, v. 264, no. 5159, p. 662-663.

Klug, Caroline; Cashman, K. V., 1994, Vesiculation of May 18, 1980, Mount St. Helens magma: Geology, v. 22, no. 5, p. 468-472.

Lackaff, B. B.; Hunt, B. J.; Von Essen, I. E., 1993, The development and implementation of a GIS-based contaminant source inventory over the Spokane aquifer, Spokane County, Washington: Water Resources Bulletin, v. 29, no. 6, p. 949-955.

Luce, C. H.; Cundy, T. W., 1994, Parameter identification for a runoff model for forest roads: Water Resources Research, v. 30, no. 4, p. 1057-1069.

MacArthur, R. C.; Hamilton, D. L.; Brunner, G. W., 1991, Numerical methods for simulating debris blockage failures and mudflows. *In* Ritter, W. F., editor, Irrigation and drainage—Proceedings of the 1991 national conference: American Society of Civil Engineers, p. 553-559.

MacKay, M. E.; Jarrard, R. D.; Westbrook, G. K.; Hyndman, R. D.; Ocean Drilling Program Leg 146 Shipboard Scientific Party, 1994, Origin of bottom-simulating reflectors—Geophysical evidence from the Cascadia accretionary prism: Geology, v. 22, no. 5, p. 459-462.

Mathewes, R. W.; Clague, J. J., 1994, Detection of large prehistoric earthquakes in the Pacific Northwest by microfossil analysis: Science, v. 264, no. 5159, p. 688-691.

McCammon, R. B.; Finch, W. I., 1993, The deposit size frequency method for estimating undiscovered uranium deposits: Nonrenewable Resources, v. 2, no. 2, p. 106-112.

Meyers, P. A.; Ishiwatari, Ryoshi, 1993, Lacustrine organic geochemistry—An overview of indicators of organic matter sources and diagenesis in lake sediments: Organic Geochemistry, v. 20, no. 7, p. 867-900.

Miller, R. B., 1994, A mid-crustal contractional stepover zone in a major strike-slip system, North Cascades, Washington: Journal of Structural Geology, v. 16, no. 1, p. 47-60.

Monastersky, Richard, 1994, Mount Rainier threatens with fire and ice: Science News, v. 145, no. 22, p. 341.

Montgomery, D. R.; Dietrich, W. E., 1994, A physically based model for the topographic control on shallow landsliding: Water Resources Research, v. 30, no. 4, p. 1153-1171.

Moran, S. C., 1994, Seismicity at Mount St. Helens, 1987–1992—Evidence for repressurization of an active magmatic system: Journal of Geophysical Research, v. 99, no. B3, p. 4341-4354.

Neele, Filip; VanDecar, J. C.; Snieder, Roel, 1993, The use of P wave amplitude data in a joint inversion with travel times for upper mantle velocity structure: Journal of Geophysical Research, v. 98, no. B7, p. 12,033-12,054.

Nelson, A. R., 1992, Holocene tidal-marsh stratigraphy in south-central Oregon—Evidence for localized sudden submergence in the Cascadia subduction zone. *In* Fletcher, C. H.; Wehmiller, J. F., editors, Quaternary coasts of the United States—Marine and lacustrine systems: SEPM (Society for Sedimentary Geology) Special Publication 48, p. 287-301.

Nelson, A. R.; Ota, Yoko; Stafford, T. W., Jr.; Umitsu, Masatomo; Kashima, Kaoru; Matsushima, Yoshiaki, 1992, High-precision accelerator-mass-spectrometer radiocarbon dating of buried tidal-marsh soils—An approach to estimating the frequency and coastal extent of subduction zone earthquakes in Oregon and Washington. *In* Weiss, A. J., compiler, Proceedings of the U.S. Nuclear Regulatory Commission 19th Water Reactor Safety Information Meeting: U.S. Nuclear Regulatory Commission NUREG/CO-0119, v. 3, p. 463-478.

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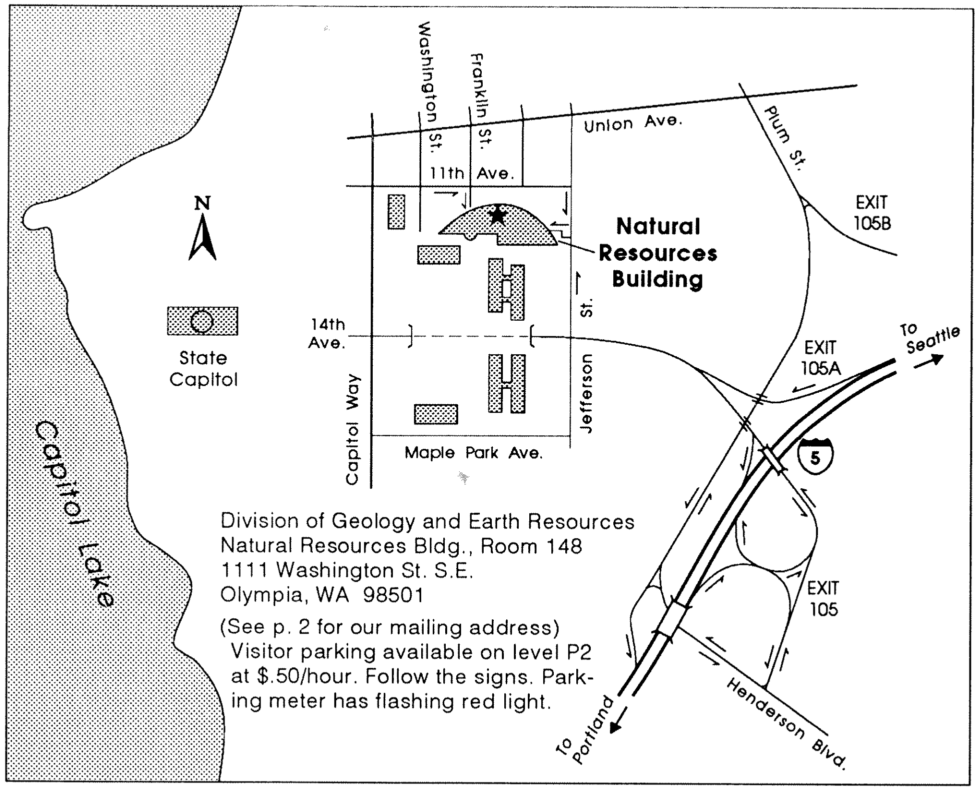

Ng, M. K.-F.; LeBlond, P. H.; Murty, T. S., 1990, Numerical simulation of tsunami amplitudes on the coast of British Columbia due to local earthquakes: Science of Tsunami Hazards, v. 8, no. 2, p. 97-127.

Papale, Paolo; Dobran, Flavio, 1994, Magma flow along the volcanic conduit during the Plinian and pyroclastic flow phases of the May 18, 1980, Mount St. Helens eruption: Journal of Geophysical Research, v. 99, no. B3, p. 4355-4373.

Payton, Jere, 1993, Community socioeconomic impacts. *In* Washington Coalition for Responsible Mining, Cyanide-leach mining in Washington—Creating a new regulatory structure for a new gold rush: Washington Coalition for Responsible Mining, p. 25-28.

Peacock, S. M.; Rushmer, Tracy; Thompson, A. B., 1994, Partial melting of subducting oceanic crust: Earth and Planetary Science Letters, v. 121, no. 1-2, p. 227-244.

Percival, J. B.; Ames, D. E., 1993, Clay mineralogy of active hydrothermal chimneys and an associated mound, Middle Valley, northern Juan de Fuca Ridge: Canadian Mineralogist, v. 31, pt. 4, p. 957-971.

Pitlick, John, 1992, Flow resistance under conditions of intense gravel transport: Water Resources Research, v. 28, no. 3, p. 891-903.

Reiter, M. L.; Beschta, R. L., 1992, Subsurface flow dynamics of a forested riparian area in the Oregon Coast Range. *In* Jones, M. E.; Laenen, Antonius, editors, Interdisciplinary approaches in hydrology and hydrogeology: American Institute of Hydrology, p. 485-501.

Rice, D. R., 1992, Oxygen on line at Kettle River. *In* Randol Gold Forum Vancouver '92—Integrating mining, metallurgical and environmental innovations for success in demanding times: Randol International Ltd., p. 271-273.

Robert, Christian; Goffe, Bruno, 1993, Zeolitization of basalts in subaqueous freshwater settings—Field observations and experimental study: Geochemica et Cosmochimica Acta, v. 57, no. 15, p. 3597-3612.

Routh, J.; Ikramuddin, Mohammed, 1994, Impact of lead-zinc mining on distribution of major and trace elements in water, sediment and soil: Society for Mining, Metallurgy, and Exploration, Inc. Preprint 94-215, 4 p.

Schumacher, Rolf, 1994, A reappraisal of Mount St. Helens' ash clusters—Depositional model from experimental observation: Journal of Volcanology and Geothermal Research, v. 59, no. 3, p. 253-260.

Scott, K. M., 1992, Risk analysis of sediment gravity flows at Cascade Range volcanoes—Approaches and analogies with alluvial fans. *In* Jones, M. E.; Laenen, Antonius, editors, Interdisciplinary approaches in hydrology and hydrogeology: American Institute of Hydrology, p. 222-230.

Sehgal, C. K.; Fischer, S. H.; Sabri, R. G., 1992, Cushman spillway modification. *In* Modification of dams to accommodate major floods; Twelfth annual USCOLD lecture series: U.S. Committee on Large Dams, p. 1-25.

Smith, D. R.; Leeman, W. P., 1993, The origin of Mount St. Helens andesites: Journal of Volcanology and Geothermal Research, v. 55, no. 3-4, p. 271-303.

Smith, R. A., 1993, Federal and state statutes and regulations on environmental and community impacts of open pit and cyanide process mining in Washington. *In* Washington Coalition for Responsible Mining, Cyanide-leach mining in Washington—Creating a new regulatory structure of a new gold rush: Washington Coalition for Responsible Mining, p. 9-15.

Sparks, R. S. J.; Stasiuk, M. V.; Gardeweg, M.; Swanson, D. A., 1993, Welded breccias in andesite lavas: Geological Society of London Journal, v. 150, pt. 5, p. 897-902.

Stednick, J. D.; Kern, T. J., 1992, Long term effects of timber harvesting in the Oregon Coast Range—The New Alsea Watershed Study (NAWS). *In* Jones, M. E.; Laenen, Antonius, editors, Interdisciplinary approaches in hydrology and hydrogeology: American Institute of Hydrology, p. 502-510.

Stevens, G. R.; Ralston, Dale, 1994, Evaluation of the ground water resources within the Lewiston Basin. *In* Link, P. K., editor, Hydrology, waste disposal, science and politics—Engineering Geology and Geotechnical Engineering, 30th Symposium, 1994: Idaho State University, p. 601-613.

Thiessen, R. L.; Johnson, K. R.; Mohl, G. B., 1992, Geophysical investigations of the cratonic margin in the Pacific Northwest (USA). *In* Bartholomew, M. J.; Hyndman, D. W.; Mogk, D. W.; Mason, Robert, editors, Basement tectonics 8—Characterization and comparison of ancient and Mesozoic continental margins; Proceedings: Kluwer Academic Publishers, p. 231-240.

Tschnerich, R. W., 1994, Zeolites from Signal Peak, Cowlitz County, Washington: Microprobe, v. 7, no. 9, p. 22-24.

Tsuboyama, Yoshio; Sidle, R. C.; Noguchi, Shoji; Hosoda, Ikuhiro, 1994, Flow and solute transport through the soil matrix and macropores of a hillslope segment: Water Resources Research, v. 30, no. 4, p. 879-890.

Turner, R. J. W.; Ames, D. E.; Franklin, J. M.; Goodfellow, W. D.; Leitch, C. H. B.; Höy, Trygve, 1993, Character of active hydrothermal mounds and nearby altered hemipelagic sediments in the hydrothermal areas of Middle Valley, northern Juan de Fuca Ridge—Data on shallow cores: Canadian Mineralogist, v. 31, pt. 4, p. 973-995.

Vaccaro, J. J.; Dinicola, R. S.; Bauer, H. H., 1992, Recognition of the interdependence of surface water and ground-water resource investigations. *In* Jones, M. E.; Laenen, Antonius, editors, Interdisciplinary approaches in hydrology and hydrogeology: American Institute of Hydrology, p. 1-8.

Varsek, J. L.; Cook, F. A., 1994, Three-dimensional crustal structure of the eastern Cordillera, southwestern Canada and northwestern United States: Geological Society of America Bulletin, v. 106, no. 6, p. 803-823.

Wang, Kelin, 1994, Kinematic models of dewatering accretionary prisms: Journal of Geophysical Research, v. 99, no. B3, p. 4429-4438.

Weaver, C. S.; Shedlock, K. M., 1994, Estimates of seismic source regions from considerations of the earthquake distribution and regional tectonics in the Pacific Northwest. *In* Applied Technology Council, Proceedings of seminar on new developments in earthquake ground motion estimation and implications for engineering design practice: Applied Technology Council, p. 5-1–5-24.

Weber, E. F.; Wilson, J.; Kirk, M.; Tochko, S., 1994, Selected remedy at the Queen City Farms superfund site—A risk management approach. *In* Link, P. K., editor, Hydrology, waste disposal, science and politics—Engineering Geology and Geotechnical Engineering, 30th Symposium, 1994: Idaho State University, p. 413-427.

Weichert, Dieter, 1994, Omak rock and the 1872 Pacific Northwest earthquake: Seismological Society of America Bulletin, v. 84, no. 2, p. 444-450.

Wheat, C. G.; Mottl, M. J., 1994, Hydrothermal circulation, Juan de Fuca Ridge eastern flank—Factors controlling basement water composition: Journal of Geophysical Research, v. 99, no. B2, p. 3067-3080.

White, D. J.; Clowes, R. M., 1994, Seismic attenuation structure beneath the Juan de Fuca Ridge from tomographic inversion of amplitudes: Journal of Geophysical Research, v. 99, no. B2, p. 3043-3056.

Whitlock, Cathy, 1992, Vegetational and climatic history of the Pacific Northwest during the last 20,000 years—Implications for understanding present-day biodiversity: Northwest Environmental Journal, v. 8, no. 1, p. 2-28.

Williamson, A. K.; Bortleson, G. C., 1992, National Water-Quality Assessment Program, central Columbia plateau, Washington and Idaho. *In* Jones, M. E.; Laenen, Antonius, editors, Interdisciplinary approaches in hydrology and hydrogeology: American Institute of Hydrology, p. 338-349.

Yuan, T.; Spence, G. D.; Hyndman, R. D., 1994, Seismic velocities and inferred porosities in the accretionary wedge sediments at the Cascadia margin: Journal of Geophysical Research, v. 99, no. B3, p. 4413-4427.

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Zabowski, Darlene; Ugolini, F. C., 1992, Seasonality in the mineral stability of a subalpine Spodosol: Soil Science, v. 154, no. 6, p. 497-507.

Zhang, Weihua; Montgomery, D. R., 1994, Digital elevation model grid size, landscape representation, and hydrologic simulations: Water Resources Research, v. 30, no. 4, p. 1019-1028. ■

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